Site-Wide Soil Gas Human Health Risk Assessment
Tronox LLC
Henderson, Nevada

November 22, 2010

Prepared For:

Tronox LLC
560 W. Lake Mead Parkway
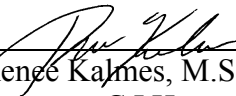Henderson, Nevada 89015

Prepared By:

Northgate Environmental Management, Inc.
300 Frank H. Ogawa Plaza, Suite 510
Oakland, California 94612
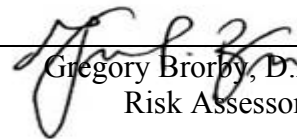
and

Exponent, Inc.
500 12th Street, Suite 220
Oakland, CA 94607

Deni Chambers, C.E.G., C.Hg.	Renee Kalmes, M.S.P.H.,	Gregory Brorby, D.A.B.T.
Principal Hydrogeologist	C.I.H.	Risk Assessor
	Risk Assessor	

2027.07

TABLE OF CONTENTS

TABLES

FIGURES

APPENDICES

ACRONYM LIST

Acronym	Meaning
AP&CC	American Potash and Chemical Company
AT	Averaging time
ATSDR	Agency for Toxic Substances Disease Registry
BCL	Basic comparison level
Bgs	Below ground surface
BMI	Black Mountain Industrial
BRC	Basic Remediation Company
Cal-EPA	California Environmental Protection Agency
CLP	Contact Laboratory Program
COC	Chain-of-custody
COPC	Chemical of potential concern
CSM	Conceptual site model
DQA	Data quality assessment
DQI	Data quality indicator
DQO	Data quality objective
DVSR	Data validation summary report
EC	Exposure concentration
ECAO	Environmental Criteria And Assessment Office
ED	Exposure duration
EDD	Electronic data deliverable
EF	Exposure frequency
EPC	Exposure-point concentration
ET	Exposure time
GC	Gas chromatograph
HEAST	Health Effects Assessment Summary Tables
HEC	Human equivalent concentration
Hg	Mercury
HI	Hazard Index
HRA	Health Risk Assessment
IAQ	Indoor air quality
ILCR	Incremental lifetime cancer risk
IRIS	Integrated Risk Information System
ITRC	Interstate Technology Regulatory Council
J&E	Johnson and Ettinger
LCS	Laboratory control sample
LOAEL	Lowest observed adverse effect level
LOU	Letter of Understanding
MDEQ	Michigan Department of Environmental Quality
MOA	Mode of action
MS	Mass spectrometer

Acronym	Meaning
NCEA	National Center for Environmental Assessment
NDEP	Nevada Division of Environmental Protection
NOAEL	No observed adverse effect level
PARCC	Precision, accuracy, representativeness, comparability, and completeness
PBPK	Physiologically-based pharmacokinetic
PNNL	Pacific Northwest National Laboratories
PPRTV	Provisional peer-reviewed toxicity value
QA	Quality assurance
QAPP	Quality Assurance Project Plan
QC	Quality control
RfC	Reference concentration
RME	Reasonable maximum exposure
RPD	Relative percent difference
RSD	Relative standard deviation
RZ	Remediation Zone
SGSSL	Soil gas site specific level
SOP	Standard operating procedure
SQL	Sample quantitation limit
SRC	Site-related chemical
SSL	Soil screening level
TCE	Trichloroethene
UCL	Upper confidence limit
URF	Unit risk factor
U.S. EPA	U.S. Environmental Protection Agency
VF	Volatilization factor
VOC	Volatile organic compound
WECCO	Western Electrochemical Company

EXECUTIVE SUMMARY

On behalf of Tronox LLC (Tronox), Northgate Environmental Management, Inc. (Northgate) and Exponent, Inc. (Exponent) have prepared this Site-Wide Soil Gas Human Health Risk Assessment (HRA) for the Tronox facility in Henderson, Nevada (the Site). This HRA has been conducted following the methods presented in the March 9, 2010 *HRA Work Plan* (Northgate, 2010a), which was approved by the Nevada Division of Environmental Protection (NDEP) on March 16, 2010. The objective of the HRA was to evaluate the potential for adverse health impacts that may occur as a result of potential exposure to chemicals in soil gas via inhalation of indoor or outdoor air.

Based on the Conceptual Site Model (CSM) for the Tronox facility, potential exposure to chemicals in soil gas was evaluated for future indoor commercial workers via inhalation of indoor air and future outdoor commercial workers via inhalation of outdoor air. Potential exposure to residual chemicals in soil at the Site and the potential for leaching of chemicals in soil to groundwater are being evaluated separately; therefore, these media were not evaluated in this report.

Soil gas data collected as part of the Phase B Source Area Investigation Soil Gas Survey were evaluated and considered useable for purposes of this HRA. Chemicals of potential concern (COPCs) were selected according to a multi-step process, including a toxicity screen, frequency of detection, and CSM considerations. Based on this process, eight chemicals (benzene, bromodichloromethane, carbon tetrachloride, chloroform, hexachlorobutadiene, naphthalene, tetrachloroethene, and trichloroethene) were selected as COPCs. The results of the HRA can be summarized as follows:

Site –Wide Findings

- Non-cancer hazard indices associated with inhalation of vapors in indoor and outdoor air and theoretical excess cancer risks associated with inhalation of vapors in outdoor air were below NDEP's point of departure (hazard index of 1 and cancer risk of 1×10^{-6}).
- Theoretical excess cancer risks associated with inhalation of vapors in indoor air range from 2×10^{-9} (SG94, located in Remediation Zone [RZ]-C) to 1×10^{-4} (SG32, also located in RZ-C). Chloroform is the largest contributor to the overall risk (up to >99%) at the majority of locations. Carbon tetrachloride also contributes to the overall risk (up to 43%) at some locations. None of the other COPCs had total excess cancer risk estimates greater than 1×10^{-6}.

Area-Specific Findings

The designation of the RZs within the main fenced Tronox facility was primarily based on soil investigation findings, which may not be the most appropriate basis for designating soil gas exposure areas. Nevertheless, risk estimates were provided for RZ-A through RZ-E as well for several parcels adjacent to the Tronox facility.

- For RZ-A and all the parcels, the estimated excess cancer risks associated with exposure of an indoor commercial worker to the COPCs in soil gas through inhalation of vapors in indoor air are at or below 1×10^{-6} and hazard index values are well below 1.
- For RZ-B, the estimated excess cancer risks associated with exposure of an indoor commercial worker to the COPCs in soil gas through inhalation of vapors in indoor air range from 5×10^{-9} to 9×10^{-5}, with the highest risk estimates near Unit Buildings 3 and 4 in the east-central portion of RZ-B. The area of higher estimated risks is consistent with higher chloroform concentrations in shallow groundwater in this area of the site.
- For RZ-C, the estimated excess cancer risks associated with exposure of an indoor commercial worker to the COPCs in soil gas through inhalation of vapors in indoor air range from 2×10^{-9} to 1×10^{-4} with the highest risk estimates clustered along the western property boundary and in the east-central portion of the site, areas that coincide with elevated concentrations of chloroform and carbon tetrachloride in shallow groundwater.
- For RZ-D, the estimated excess cancer risks associated with exposure of an indoor commercial worker to the COPCs in soil gas through inhalation of vapors in indoor air range from 5×10^{-8} to 2×10^{-5} with the high risk estimates clustered along the western property boundary, which again coincides with elevated concentrations of chloroform in shallow groundwater.
- For RZ-E, there are only two soil gas sampling locations and the total excess cancer risks associated with exposure of an indoor commercial worker to the COPCs in soil gas through inhalation of vapors in indoor air at both of these locations is 3×10^{-6}.

There are multiple sources of uncertainty associated with the HRA results, particularly regarding model predictions of indoor air concentrations. Site-specific data were used when possible to reduce uncertainty. There is relatively little guidance on appropriate values for two parameters, i.e., air exchange rate and the vapor flow rate into commercial buildings. The above results are based on conservative (i.e., heath-protective) assumptions for these two parameters. If less conservative, but still reasonable, assumptions are used, the estimated excess cancer risks and

non-cancer hazard indices are a factor of four lower (i.e., on a site-wide basis, excess cancer risks drange from 6×10^{-10} to 3×10^{-5}).

Data usability and data quality assessments indicate that sufficient data are available to support the results of this HRA.   Findings from this site-wide soil gas HRA will be incorporated into the RZ and parcel-specific risk assessments, as appropriate, to allow for risk management decisions.

1.0   INTRODUCTION

On behalf of Tronox LLC (Tronox), Northgate Environmental Management, Inc. (Northgate) and Exponent, Inc. (Exponent) have prepared this Site-Wide Soil Gas Human Health Risk Assessment (HRA) for the Tronox facility in Henderson, Nevada (the Site). This HRA has been conducted following the methods presented in the March 9, 2010 *HRA Work Plan* (Northgate, 2010a), which was approved by the Nevada Division of Environmental Protection (NDEP) on March 16, 2010.

1.1   Site Description and History

The approximately 450-acre Site is located approximately 13 miles southeast of the city of Las Vegas in an unincorporated area of Clark County, Nevada, and lies in Sections 1, 12, and 13 of Township 22 S, Range 62 E, (see Figure 1). The site is located within the Black Mountain Industrial (BMI) complex, which consists of several facilities, owned and operated by chemical companies, one of which is Tronox. The City of Henderson surrounds the BMI complex, which is an unincorporated Clark County "island."

The BMI complex was first developed by the U.S. government in 1942 as a magnesium plant for World War II operations. Later, a part of the BMI complex was leased by Western Electrochemical Company (WECCO), which would ultimately become the Tronox Site. WECCO produced manganese dioxide, sodium chlorate, sodium perchlorate, and other perchlorates. WECCO also produced ammonium perchlorate (a powerful oxidizer) for the Navy during the early 1950s using a plant that was constructed on the Site by the Navy. WECCO merged with American Potash and Chemical Company (AP&CC) in 1956, which continued production of ammonium perchlorate for the Navy. In 1967, AP&CC merged with Kerr-McGee Corporation (Kerr-McGee) and added production of boron chemicals in the early 1970s. The production processes included elemental boron, boron trichloride (a colorless gas used as a reagent in organic synthesis), and boron tribromide (a colorless fuming liquid compound used in a variety of applications). The production of boron tribromide was discontinued in 1994, and the production of sodium chlorate and ammonium perchlorate was discontinued in 1997 and 1998, respectively. Perchlorate was reclaimed at the Site using existing equipment until early 2002.

In 2005, Kerr-McGee Chemical LLC was renamed Tronox LLC. Tronox's Henderson facility continues to produce electrolytic manganese dioxide, used in the manufacture of alkaline batteries; elemental boron, a component of automotive airbag igniters; and boron trichloride,

used in the pharmaceutical and semiconductor industries and in the manufacture of high-strength boron fibers for products that include sporting equipment and aircraft parts.

During the 1970s, the U.S. Environmental Protection Agency (U.S. EPA), the State of Nevada, and Clark County investigated potential environmental impacts from the BMI companies' operations, including atmospheric emissions, groundwater and surface-water discharges, and soil impacts (Ecology and Environment, 1982). From 1971 to 1976, Kerr-McGee modified its manufacturing process and constructed lined surface impoundments to recycle and evaporate industrial wastewater. In 1976, the facility achieved zero discharge status regarding industrial wastewater management. In 1980, the U.S. EPA requested specific information from the BMI companies regarding their manufacturing and waste management practices by issuing Section 308 letters. In 1993, a Phase I site assessment was completed for the Site and approved by NDEP. In 1994, NDEP issued a Letter of Understanding (LOU) to Kerr-McGee that identified 69 specific areas or items of interest and indicated the level of environmental investigation they wanted Kerr-McGee to conduct. In 1996, Kerr-McGee completed a Phase II site assessment, which included field sampling as described in an NDEP-approved Phase II Work Plan.

Tronox has continued to undertake environmental investigations to assess environmental conditions at the Henderson facility. A detailed discussion of the specific areas or items of interest identified in the LOU, and a list of the products made, years of production, and approximate waste volumes for WECCO, AP&CC, and Tronox are found in the *Conceptual Site Model (CSM) Report* (ENSR, 2005).

Background information, including local geology, hydrogeology, and wind direction, is also described in the *Conceptual Site Model (CSM) Report* (ENSR, 2005). In general, groundwater is encountered in the fine-grained facies within the uppermost Muddy Creek Formation. The depth to groundwater ranges from about 27 to 80 feet below ground surface (bgs) and is generally deepest in the southernmost portion of the Site. The prevailing wind direction for the site is from the Southwest and the South or West with the Olin property located up-wind (west) and the Timet property located down-wind (east) from the Site (see Figure 1 for wind-rose). Based on the prevailing wind direction, the nearest down-wind residences are located approximately 300 feet from the northern parcels (Parcels A and I), but more than 2000 feet from the fenced main Tronox facility.

1.2   Overview of Site Investigation

The details of the soil gas sampling at the Site are provided in the *Phase B Source Area Investigation Soil Gas Survey Work Plan* (Soil Gas Work Plan; ENSR 2008a), which was approved by NDEP in March 2008. Briefly, soil gas samples were collected at 95 locations across the site as shown on Figure 2; field duplicates were collected at 10 locations. The majority of these locations are within the fenced main Tronox facility; however, several soil gas samples were also collected from locations within several adjacent parcels, some of which have been investigated by the Basic Remediation Company (BRC) independent of Tronox's Source Area investigation. Sample locations were based on the *Phase A Source Area Investigation Results* (ENSR, 2007), which identified the presence of several volatile organic compounds (VOCs) in soil and/or groundwater at the Site, including chloroform and trichloroethene (TCE); historic soil and groundwater data collected from prior investigations; and from groundwater studies performed since the Phase A investigation by Hargis + Associates (2008) as part of their work for companies located west of the Tronox facility.

1.3   Scope of the Site-Wide Soil Gas Health Risk Assessment

The objective of this HRA is to evaluate the potential for adverse human health impacts that may occur as a result of potential exposures to chemicals in soil gas via inhalation of indoor or outdoor air. As presented in the approved *HRA Work Plan* (Northgate, 2010a), potential exposure to residual chemicals in soil and potential for leaching of chemicals in soil to groundwater are being evaluated separately; therefore, these media are not evaluated in this report. Following completion of these assessments, the cumulative risks from soil and soil gas will be documented for risk management decisions. Additionally, consistent with the *HRA Work Plan*, ecological habitat is not currently sufficient to warrant an ecological risk assessment, nor will it be in the future.

The HRA follows the basic procedures outlined in the U.S. EPA's *Risk Assessment Guidance for Superfund: Volume I—Human Health Evaluation Manual* (U.S. EPA, 1989). Other guidance documents consulted in formulating the risk assessment include:

- Guidelines for Exposure Assessment (U.S. EPA, 1992a).
- Exposure Factors Handbook (U.S. EPA, 1997).
- Supplemental Guidance for Developing Soil Screening Levels for Superfund Sites (U.S. EPA, 2002).

- Nevada Administrative Code Chapter NAC 445A. Adopted Permanent Regulation of the Nevada State Environmental Commission. LCB File No. R119-96 (NDEP 1996).

- Risk Assessment Guidance for Superfund, Volume I: Human Health Evaluation Manual (Part F, Supplemental Guidance for Inhalation Risk Assessment) (U.S. EPA, 2009).

1.4   Organization of Report

The remainder of this assessment is organized as follows:

- **Section 2, Exposure Scenarios and Conceptual Site Model:** This section describes the relationships between the suspected sources of chemicals identified at the Site, the mechanisms by which the chemicals might be released and transported in the environment, and the means by which the receptors could come in contact with the chemicals, and presents the CSM.

- **Section 3, Data Evaluation, Usability, and Selection of Chemicals of Potential Concern:** This section discusses the sources of analytical data that are used in the HRA and procedures used to evaluate the data and select the chemicals of potential concern (COPCs).

- **Section 4, Exposure Assessment:** This section presents the equations and input values used to calculate potential exposure for each of the identified COPCs.

- **Section 5, Toxicity Assessment:** This section presents the toxicity criteria used to evaluate the COPCs.

- **Section 6, Risk Characterization:** The risk characterization section presents the estimated risks and hazard indices associated with potential exposure to the COPCs for the scenarios evaluated. In addition, an uncertainty analysis discusses the relative impact of the primary assumptions used in the assessment.

- **Section 7, Conclusions:** This section summarizes the conclusions of the report.

- **Section 8, References:** This section provides complete references for the literature cited throughout the report.

2.0 EXPOSURE SCENARIOS AND CONCEPTUAL SITE MODEL

The exposure scenarios considered in this HRA are dependent on the relevant exposure pathways and receptor populations for the Tronox facility. The CSM is a tool used in risk assessment to describe relationships between chemicals and potentially exposed human receptor populations, thereby delineating the relationships between the suspected sources of chemicals identified at the Site, the mechanisms by which the chemicals might be released and transported in the environment, and the means by which the receptors could come in contact with the chemicals. The CSM provides a basis for defining data quality objectives (DQOs), guiding site characterization, and developing exposure scenarios.

2.1 Sources and Release Mechanisms

As described in the Soil Gas Work Plan (ENSR, 2008a), the Phase A Source Area investigation focused on soil and groundwater conditions associated with site-related chemicals (SRCs), including VOCs, and their suspected source areas. VOCs were reported sporadically in the Phase A soil samples (ENSR, 2007). Chloroform was detected most frequently (~50% of the samples) and generally at depths below 15 to 20 ft bgs, which is consistent with the presence and distribution of chloroform in groundwater. The Phase A investigation samples revealed a plume of chloroform, and to a lesser extent TCE, in groundwater located in the central portion of the Site, potentially emanating from the Unit 3 and Unit 4 buildings, and another plume of VOCs, principally chloroform and to a lesser extent benzene, located along the western site boundary, possibly from an off-site source to the west (ENSR, 2007). The results from the Phase B soil and groundwater investigations are generally consistent with these results.

From a review of historic information and Phase A investigation results, the following areas were identified in the Soil Gas Work Plan as potential sources of VOCs or areas where VOCs had been detected in soil and/or groundwater (ENSR, 2008a):

- Former Hardesty Chemical Company site (LOU 4)
- Onsite portion of the Beta Ditch, including small diversion ditches (LOU 5)
- Old P-2, Old P-3, and New P-2 Ponds, and Ponds S-1 and P-1 (LOUs 7, 8, 9, 13, and 14)
- Ponds AP-1 through AP-5 (LOUs 16, 17, 18, and 19)
- Former Truck Emptying/Dumping Site (LOU 35)
- Satellite Accumulation Point/AP Maintenance Shop (LOU 39
- Unit 4 Basement and Old Sodium Chlorate Plant Decommissioning (LOU 43)

- Diesel Storage Tank Area (LOU 45)

- AP Plant Area Change House/Laboratory Septic Tank (LOU 54)

- Acid Drain System (LOU 60)

- Former State Industries, including impoundments and catch basin (LOU 62)

- Southern Nevada Auto Parts site (Pick-a-Part) (LOU 68)

Potential release mechanisms from above-ground source areas, such as spills, leaks, or accidents, could have released VOCs to surface soils. These VOCs may have then leached into subsurface soils and eventually migrated to groundwater. In addition, subsurface sources such as below-ground piping may have released VOCs to the subsurface that may subsequently have migrated to groundwater via leaks or accidents. Finally, chemicals in off-site groundwater appear to be migrating onto the Tronox facility along the western property boundary. In addition to the potential primary release mechanisms, secondary release mechanisms may include volatilization of chemicals in groundwater and soil into indoor or outdoor air.

2.2   Potential Receptors and Exposure Pathways

The identification of potentially exposed populations and exposure pathways is supported by the CSM. For a complete exposure pathway to exist, each of the following elements must be present (U.S. EPA, 1989):

- A source and mechanism for chemical release;

- An environmental transport medium (i.e., air, water, soil);

- A point of potential human contact with the medium; and

- A route of exposure (e.g., inhalation, ingestion, dermal contact).

As discussed previously, the Site is a currently-operating industrial facility. In the future, the Site will continue to be used for industrial and/or commercial purposes. Accordingly, for purposes of evaluating long-term exposure to VOCs in indoor or outdoor air, current and future "on-Site receptors" include long-term indoor workers and long-term outdoor workers (U.S. EPA, 2002). Other potential on-Site receptors, such as visitors or trespassers, do not warrant assessment. As discussed by U.S. EPA (2002), evaluation of exposures to members of the public under a non-residential land-use scenario is not warranted for two reasons:

1. Public access is generally restricted at industrial sites, and

2. While the public may have access to commercial sites, on-site workers have a much higher exposure potential, as they spend substantially more time at a site.

Finally, it is possible that short-term construction workers may be exposed to VOCs in outdoor air. This exposure pathway may be of particular concern when high concentrations of VOCs are present in surface soil and construction activities can enhance the volatilization of these chemicals into the outdoor air (U.S. EPA, 2002). However, this is not the case at the Tronox facility because VOCs are generally not present in near surface soil and the source of chemicals to outdoor air is primarily affected groundwater. As such, the magnitude of exposure to VOCs in outdoor air by short-term construction workers is expected to be substantially lower than that estimated for long-term outdoor workers and was not evaluated separately in this HRA.

2.3 Conceptual Site Model

Based on the source and release mechanisms identified above, Figure 3 presents the following exposure pathway and receptor populations that are considered in the HRA:

- Indoor commercial workers
    - Indoor inhalation of VOCs from soil and groundwater
- Outdoor commercial workers
    - Outdoor inhalation of VOCs from soil and groundwater

As noted in the approved *HRA Work Plan* (Northgate, 2010a), outdoor inhalation of VOCs from soil and groundwater will be quantitatively evaluated only if warranted based on indoor exposures because modeled indoor air concentrations will be substantially greater than modeled outdoor air concentrations.

3.0 DATA EVALUATION, USABILITY, AND SELECTION OF CHEMICALS OF POTENTIAL CONCERN

This section discusses the soil gas investigation program and procedures, sources of analytical data that are used in this HRA, and procedures used to evaluate the data (data usability) and to select COPCs.

3.1 Soil Gas Sampling Investigation Program and Procedures

Soil gas samples were collected as part of the Phase B investigation in accordance with the Soil Gas Work Plan (ENSR, 2008a). This investigation is the sole source of soil gas data included in this HRA. As specified in the Soil Gas Work Plan, soil gas samples were collected using direct-push technology. Temporary soil gas probes were installed using a track-mounted Geoprobe rig. Soil gas sampling procedures followed the methods described in BRC's Standard Operating Procedure (SOP) 37- Active Soil Gas Investigation (ERM and MWH, 2007). Soil gas samples were collected into six-liter Summa canisters and analyzed for VOCs according to EPA Method TO-15. Although the Work Plan indicated that most samples were to be collected from 10 feet bgs, the procedure was modified to generally collect samples at 5 feet bgs, which is consistent with SOP 37. In the vicinity of Unit Building 3, Unit Building 5 and Unit Building 6, four samples were obtained at 20 feet bgs (SG-36, SG-37, SG-38 and SG-41). SG-41 was obtained near Unit Building 3 where the basement is occupied with engineering staff.

To ensure that ambient air was removed from the sample train and that soil gas samples were characteristic of subsurface conditions, a purge volume versus contaminant concentrate test was performed at SG83 near the western boundary of the Site. Stepped purge tests of one, three and seven purge-volumes were conducted on samples from SG83 to determine purge volumes to be applied to the remainder of the sampling. As shown in the Data Validation Summary Report (DVSR) soil gas table ("Volatile Organic Compounds and Helium Concentrations in Soil Gas"), the VOC concentrations were similar for the three different purge volumes (ENSR, 2008b). Based on these results, ENSR reported that three sample train volumes was chosen as the standard volume to be purged prior to collection of soil gas form the rest of the Site.

Helium was used at each sample location as a tracer gas or leak-check compound as a means of checking for leaks during collection of soil gas samples. Ambient air has the potential to leak into the sampling system during sampling, which could dilute samples and produce results that underestimate actual Site conditions or contaminate the sample with external contaminants. Leakage can potentially occur at sample system connections, at surface seals (i.e., around rods and tubing), or at the top of the temporary soil gas probes. Accordingly, a shroud was placed

over the sampling apparatus, helium was introduced into the shroud and the concentration measured. When helium was detected in the soil gas sample at a concentration above 1% of the concentration in the shroud, a second soil gas sample was collected to replace the original sample. All helium samples were analyzed by EPA Method 3C (ENSR, 2008a,b). As discussed in the DVSR correspondence with NDEP on this issue (Attachment C of DVSR), the Interstate Technology Regulatory Council (ITRC) lists helium as an acceptable tracer compound for soil gas surveys (ITRC, 2007). Additionally, the presence of helium in a sample will not interfere with the TO-15 VOC analysis and the required reporting limits can still be achieved.

As reported by ENSR, a leak check was performed to ensure that there were no leaks of ambient air along the sample train. With the Summa™ canister valve closed and the valve connecting the subsurface portion of the sample tubing also closed, the leak check consisted of creating a vacuum (30-inches of mercury [Hg]) along the sample train for at least 5 minutes while monitoring the in-line vacuum gauge. Once the leak-check test confirmed that there were no leaks along the sample train, the canister valve and the valve leading to the subsurface sample tubing were opened and the Summa™ canister was filled with soil gas. The filled Summa™ canister was labeled and logged on chain-of-custody (COC) forms. The canisters were shipped to Columbia Analytical Services – Air Laboratory in Simi Valley, California. Appendix A contains the soil gas sampling field data and survey photographs.

3.2   Data Usability

The primary objective of the data usability evaluation is to identify appropriate data for use in the HRA. Evaluation of the site-wide soil gas analytical data in terms of usability for this assessment, was conducted in accordance with the criteria presented in the *Guidance for Data Usability in Risk Assessment (Parts A and B)* (U.S. EPA, 1992b,c) and the *NDEP September 2010 Revised Data Usability Guidance, BMI Plant Sites and Common Areas Projects, Henderson, Nevada* (NDEP, 2010a). These criteria include and are discussed in detail below:

- Reports to risk assessors
- Documentation review
- Data sources
- Analytical methods and detection limits
- Data review
- Data quality indicators

3.2.1 Criterion I –Reports to Risk Assessors

The usability analysis of the site characterization data requires the availability of sufficient data for review. The required information is available from the following documentation associated with the site data and data collection efforts:

- A property description is provided in the Soil Gas Work Plan (ENSR, 2008a). The Phase B Investigation Work Plan for Areas I, II, III and IV (AECOM, 2008) also identifies the location and features of the property, the characteristics of the vicinity, and contaminant transport mechanisms.

- A site map with sample locations and sampling design and procedures were provided in the Soil Gas Work Plan (ENSR, 2008a) and is also provided as Figure 2 to this report.

- Data are presented in the Revised DVSR (ENSR, 2008b, attached as Appendix B). Soil gas samples were collected from May 7 through May 29, 2008. Validation of laboratory data was completed by August 19, 2008 and a draft DVSR was submitted to NDEP on August 25, 2008. NDEP provided comments to the draft DVSR on September 18, 2008 and September 30, 2008. Tronox provided responses to NDEP comments on September 29, 2008, and submitted a revised DVSR submitted on October 13, 2008. The Revised DVSR was approved by NDEP on October 20, 2008.

- The laboratory provided a quality assurance/quality control (QA/QC) narrative with each analytical data package, and the data review provides a narrative of qualified analytical results. A description of the analytical methods and detection limits are included. These narratives are included as part of the Revised DVSR.

- Method-specific QC results are provided in each laboratory report, along with associated raw data. The laboratory reports and QC results are included as part of the Revised DVSR.

- Data flags used by the laboratory were defined adequately and are further discussed in below.

- Laboratory reports include the name and address of the laboratory, unique identification of the test report, client and project name, and dates of sample receipt and analysis. Each analytical report describes the analytical method used, and provides results on a sample-by-sample basis along with sample-specific quantitation limits (SQLs), gas chromatography/mass spectroscopy (GC/MS) tuning, initial and continuing calibrations, method and canister blanks, surrogate spike recoveries, internal standard results, laboratory control samples, field duplicate results, laboratory duplicate results, target compound identification and dilution factors. Reported sample analysis results were imported into the project database.

The Revised DVSR and accompanying lab reports (ENSR, 2008b) and the Soil Gas Survey Work Plan (ENSR, 2008a) were considered complete for HRA purposes.

3.2.2   Criterion II – Documentation Review

The objective of the documentation review is to confirm that the analytical results provided are associated with a specific sample location and collection procedure, using available documentation. For the purposes of this data usability analysis, the COC forms prepared in the field were reviewed and compared to the analytical data results provided by the laboratory to ensure completeness of the data set. Based on the documentation review, all samples analyzed by the laboratory were correlated to the correct geographic location at the property.   All soil gas locations were surveyed as described in BRC SOP-10 (ERM and MWH 2007).   Reviewed reports provide adequate information regarding sample results related to location and sampling procedures.

3.2.3   Criterion III – Data Sources

The review of data sources is performed to ensure that the analytical techniques are appropriate to identify the COPCs, appropriate analytical methods have been used and that adequate sample coverage of source areas has been obtained.   Soil gas samples were collected from a total of 95 locations across the Tronox facility and within several additional adjacent parcels. The soil gas sampling locations are shown in Figure 2. Soil gas samples were analyzed for VOCs by EPA Method TO-15, which includes 71 analytes. The placement of the site-wide sample locations was based on review of Phase A soil data (ENSR, 2007) and historical groundwater data collected from prior investigations (Hargis + Associates, 2008). VOCs were not reported frequently in the Phase A soil samples (ENSR, 2007) and this was confirmed by the Phase B soil results.

As noted in the CSM discussion (Section 2), soil gas locations were placed at LOUs where VOCs may have been used in past operations.   Soil gas locations were also selected to evaluate potential on-site and western off-site site boundary groundwater plumes, while other locations were spread randomly throughout the site to obtain overall coverage. Some soil gas locations were co-located near groundwater monitoring wells. The placement of the soil gas sample locations was deemed representative to evaluate site-wide soil gas conditions in context of the CSM.

3.2.4   Criterion IV – Analytical Methods and Detection Limits

In addition to the appropriateness of the analytical techniques evaluated as part of Criterion III, it is necessary to evaluate whether the detection limits are low enough to allow adequate

characterization of risks. At a minimum, this data usability criterion can be met through the determination that routine U.S. EPA reference analytical methods were used in analyzing samples collected from the property. The SQL for each soil gas analyte was presented in the Soil Gas Work Plan (ENSR, 2008a) and the *Quality Assurance Project Plan* (QAPP) (ENSR, 2008c). NDEP Basic Comparison Levels (BCLs) do not currently exist for soil gas. Therefore, as described in the Soil Gas Work Plan, the SQL was compared to a soil gas comparison level that was set as equal to the U.S. EPA Preliminary Remediation Goal for Ambient Air with U.S. EPA's default attenuation factor of 0.1 applied and further adjusted by dividing the level by a factor of 10, as requested by NDEP. As further discussed in Section 3.4 of this report, Soil Gas Site Specific Levels (SGSSLs) were calculated as part of this HRA for the COPC selection process and to ensure that detection limits were low enough to allow for adequate characterization of risks. Based on review of this information, method detection limits were confirmed to be adequate for risk assessment applications.

3.2.5   Criterion V – Data Review

The laboratory results for the Phase B Source Area Investigation Soil Gas Survey were subjected to formal data validation following the guidance on data validation provided by NDEP for the BMI Plant Sites (NDEP, 2006). The data from the laboratory were submitted as Contract Laboratory Program (CLP)-like data packages in PDF format and EQuIS® format electronic data deliverables (EDDs). The EDDs were imported into an EQuIS® database specifically created for this project. ENSR validated the data using the PDF data packages plus EDDs and subsequently entered the validation qualifiers into the database. Results were compared to the goals stated in the Soil Gas Work Plan (ENSR, 2008a) and QAPP (ENSR, 2008c).

The quality of the analytical results was reviewed by Renee Kalmes, CIH, and Gregory Brorby, DABT, of Exponent. As part of the Revised DVSR, individual validation memoranda were developed for batches of soil gas samples (ENSR, 2008b). Appendix B of the DVSR presents these documents. Exponent reviewed all seven of the ENSR validation memoranda that reported on the following data elements:

- Agreement of analyses conducted with COC requests
- Data package completeness
- Holding times
- Initial and continuing calibrations
- Method blanks/canister blanks

- Surrogate spike recoveries

- Internal standard results

- Laboratory Control Sample results

- Field duplicate results

- Laboratory duplicate results

- Quantitation limits and sample results

- Helium trace gas concentrations

The following summarizes the qualification findings as presented in the Revised DVSR with regard to blank contamination, calibrations, field duplicates, quantitation problems and helium tracer results.

DVSR Table Number	Title	Findings
E-4	Qualification Based on Blank Contamination	A total of 115 sample results were negated (i.e., qualified U) based on the presence of low levels of the common laboratory contaminants methylene chloride, acetone, and 2-butanone, as well as trace levels of benzene, carbon disulfide, ethanol, isopropyl benzene, naphthalene, and vinyl acetate in the method blanks. The majority of these negations were based on the presence of acetone. Target compounds were not in the canister blanks. The samples were collected in canisters verified as clean by the laboratory through routine checks of ten percent of the canisters cleaned.
E-5	Qualification based on Calibration Criteria Exceedances	One positive and nine non-detect results for 1,2-dichlorobenzene were qualified as estimated (J and UJ, respectively) due to the associated initial calibration's % relative standard deviation (RSD) for this compound, which slightly exceeded the method-defined criteria.
E-6	Qualifications based on Field Duplicate Precision	A total of 84 associated field sample result values in nine sample/field duplicate pairs were qualified as estimated (J) based on field duplicate result relative percent differences (RPDs) that exceeded the QAPP criteria. Twenty two different analytes and from two to ten records per analyte were qualified.
E-7	Qualifications based on Quantitation Problems	A total of 25 samples were qualified based on the laboratory qualifier M indicating a possible high bias due to matrix interferences in the GC/MS data. No other quantitation problems were discovered during data validation.
E-8 & E-9	Qualifications based on helium tracer concentrations	The limit is calculated as 1% of the helium concentration in the surface shroud. Four sample data sets were qualified as estimated (J) and one was rejected (R). All but one sample was re-collected later and helium was not detected. With the exception of the one sample, the re-collected data were used in the HRA (See Table E-8). See further discussion under "representativeness."

3.2.6 Criterion VI – Data Quality Indicators

Data quality indicators (DQIs) are used to verify that sampling and analytical systems used in support of project activities are in control and that the quality of the data generated for this project is appropriate for making decisions affecting future activities. No data were qualified as estimated with a low bias (J-). The DQIs address the field and analytical data quality aspects as they affect uncertainties in the data collected for site characterization and risk assessment. The DQIs include "precision", "accuracy", "representativeness", "comparability", and "completeness" (PARCC). The project QAPP provides the definitions and specific criteria for assessing DQIs using field and laboratory QC samples and is the basis for determining the overall quality of the data set. Data validation activities included the evaluation of PARCC parameters, and all data not meeting the established PARCC criteria were qualified during the validation process using the guidelines presented in the Tronox QAPP (ENSR, 2008c).

"Precision" is a measure of the degree of agreement between replicate measurements of the same source or sample. Precision is expressed by RPD between replicate measurements. Replicate measurements can be made on the same sample or on two samples from the same source. Field precision for the soil gas samples was assessed by evaluating the field duplicate results. Field duplicate samples were collected at 10 locations (i.e., SG07, SG26, SG28, SG40, SG41, SG51, SG53, SG56, SG65, and SG83). As indicated above, twenty two different analytes and from two to ten records per analytes were qualified as estimated (J).   The primary soil gas constituents of interest, chloroform, had RPDs well below the established QAPP of 50% RPD for soil gas, ranging from 0 to 22% RPD. Laboratory precision was assessed through the RPD results for matrix duplicates. Laboratory duplicates were performed on SG83B-05-07, SG56B-05, SG43B-05, SG35B-05, SG68B-05, SG27B-05, and SG78B-05[1]. The laboratory duplicate precision was acceptable and no results were qualified during validation. In total, a limited data set was qualified as estimated but usable and represents only 1% of the total field sample results dataset.

"Accuracy" measures the level of bias that an analytical method or measurement exhibits. Several QC parameters are used to evaluate the accuracy of reported analytical results:

- Holding times;
- Method Blanks;
- Surrogate spike recovery; and

---

[1] As indicated in data validation memo "TH536to15wwb," SG78B-05 was reanalyzed because RPDs for selected compounds exceeded acceptance criteria. Upon reanalysis all criteria were met.

- Laboratory Control Sample (LCS) percent recovery.

All samples were analyzed within the method-specified holding time. As indicated above, low levels of the common laboratory contaminants were detected in some method blanks. Blank result validation represents 1.4% of the total data points collected.   No target compounds were detected in canister blanks. Surrogate percent recovery met the QC acceptance criteria for all samples in the data set. The LCS percent recoveries met the QC acceptance limits of 70-130% for all sample analyses. No data were qualified as estimated with a low bias (J-).

 "Representativeness" is the degree to which data accurately and precisely represent a characteristic of the population at a sampling point or an environmental condition. There is no standard method or formula for evaluating representativeness, which is a qualitative term. "Representativeness" is achieved through selection of sampling locations that are appropriate relative to the objective of the specific sampling task, and by collection of an adequate number of samples from relevant types of locations. As noted in the CSM discussion (Section 2), soil gas locations were placed at LOUs where VOCs may have been used in past operations.   Soil gas locations were also selected to evaluate potential on-site and western off-site site boundary groundwater plumes, while other locations were spread randomly throughout the site to obtain overall coverage. Some soil gas locations were co-located near groundwater monitoring wells. The placement of the soil gas sample locations was deemed representative to evaluate site-wide soil gas conditions in context of the CSM.

The possible entrainment of contaminants and dilution of surface air could impact the representativeness of the soil gas samples. Helium, which was used as a tracer gas, was detected at concentrations greater than 1% of that detected in the shroud at four locations (SG42, SG53, SG60, and SG94). If the helium concentration was between 1% and 10% of the shroud average, then the TO-15 VOC analyte results were qualified as estimated (J) based on the possible contamination and dilution by surface air. If the helium concentration exceeded 10% of the shroud average, then the results were rejected (R). Four sample datasets were qualified as estimated and one was rejected based on these criteria. A replacement soil gas sample was collected from all but one of these locations and helium was not detected in these replacement samples (indicated by an R in the sample ID). Therefore, TO-15 data from only a single location (SG17B) were potentially impacted by surface air contamination/dilution. A comparison of the original and replacement sample results (e.g. sample SG53B-05, its duplicate SG53B-05D, the re-placement sample SG53BR-05, and its duplicate SG53BR-05D) indicates the TO-15 analyte results are very consistent regardless of the helium tracer results. This confirms that the assumptions used for data qualification based on helium tracer results were conservative and the

data quality is not significantly impacted when helium results are less than 10% of the surface shroud levels. As further discussed in Section 3.3, the replacement samples that did now show elevated helium concentrations were used in the HRA.

"Completeness" is measured by the total number of acceptable data points and total number of samples collected by source area and exposure area. Field completeness is defined as the percentage of samples actually collected versus those intended to be collected per the Soil Gas Work Plan (ENSR, 2008a). The goal stated in the QAPP for this project was greater than 90% field completeness (ENSR, 2008b). A comparison of the Soil Gas Work Plan sample tables with the database sample IDs indicates that actual field completeness was 100%, exceeding the goal established for the project. This field completeness calculation is based on the total sample locations scheduled in the Soil Gas Work Plan compared to the COC requests sent to the laboratories. All COC requests were faithfully executed by the laboratories, with minor exceptions detailed in the data validation memoranda. Laboratory completeness is defined as percentage of valid data points versus the total expected from the laboratory analyses. The objective stated in the QAPP for this project was greater than 95% laboratory completeness. Actual laboratory completeness was 100% on the basis of sample analysis (i.e., all requested analyses were performed and reported by the laboratories), and 99% completeness based on valid data.

"Comparability" is a qualitative characteristic expressing the confidence with which one data set can be combined with another for purposes of estimating exposure. Comparability is a qualitative expression of the measure of confidence that two or more data sets may contribute to a common analysis. Because this project was an initial site investigation for all of the TO-15 parameters, involving new soil gas sampling locations, there was no historical data set for comparisons. Comparability of data within the investigation was maximized by using standard methods for sampling and analysis, reporting data, and data validation. A single laboratory performed all the analyses to eliminate inter-laboratory variability

3.2.7   Data Usability Conclusions

Evaluation of the soil gas analytical data in terms of usability for the HRA was conducted in accordance with U.S. EPA and NDEP guidance. A small number of data points (6% of the total analytical dataset) were found to be qualified based on minor method blank, field duplicate, and quantitation issues but were deemed acceptable and were not biased low. All results for a single sample were rejected based on helium tracer concentrations and this sample was successfully replaced.   Based on the evaluation, all Data Usability requirements were met and, with the

exception of the single sample for which data were rejected, all soil gas data were deemed to be usable for risk assessment

3.3   Summary of Site-Wide Soil Gas Data Used in HRA

As described in Section 3.1, soil gas samples were collected from a total of 95 locations across the main fenced Tronox facility and within several additional adjacent parcels. The soil gas sampling locations are shown in Figure 2. Soil gas samples were analyzed for VOCs by EPA Method TO-15, which includes 71 analytes. A complete set of validated soil gas data for use in the HRA is provided in Appendix C. As discussed above, field duplicate samples were collected at 10 locations.   For purposes of this HRA, the data from the field duplicate samples were evaluated in the data usability discussion above; however, only the data from the primary samples were used in the risk assessment calculations. This is consistent with Option1 in the NDEP guidance for Field Duplicates and Field Splits (NDEP 2008a).   Specifically, evaluation of the primary soil gas constituents of interest (i.e., chloroform, carbon tetrachloride and TCE) all showed low RPD values between the primary and duplicate sample results and there was no clear pattern indicating that the original result was lower than that the duplicate result. Therefore, use of the primary sample was considered adequately protective from a risk perspective.

 In addition, as discussed above, a second sample was collected at the four sample locations in which helium was detected at concentrations greater than 1% of that detected in the shroud and the measured helium concentrations were not elevated; therefore, the data from the second sample was used in the risk assessment calculations. At one of these four locations, a field duplicate was collected during this second sampling event. Consistent with the other locations at which field duplicate samples were collected, the primary sample was used in the risk calculations. Finally, a second sample and field duplicate were collected at location SG65; however, the reason for collecting these samples is unknown. Because results of the original primary sample and its field duplicate and the second primary sample and its field duplicate were comparable and there was no other apparent reason as to why a second sample was collected at this location, the data for the original primary sample were used in the risk assessment calculations.

The soil gas data used in the HRA are summarized in Table 1, including the number of samples, number of detections, minimum and maximum detections, minimum and maximum detection limits, mean, median, standard deviation, and location of maximum detection. Consistent with NDEP (2008b) guidance, one-half the limit of detection was used in calculating the mean, median, and standard deviation; the sample quantitation limit (SQL) was used as the detection limit. Table 1 also includes SGSSLs and the number of detections or detection limits greater than

this value or 10% of this value. SGSSLs were calculated for this HRA because NDEP has not developed BCLs for soil gas.

The SGSSLs were calculated according to the methodology described in Section 4.1.1, assuming a theoretical lifetime excess cancer risk of 1×10^{-6} or a non-cancer hazard index of 1; calculation spreadsheets are provided in Appendix D. SGSSLs could not be calculated for six chemicals due to the absence of regulatory toxicity criteria. Five of these chemicals (1,2-dibromo-3-chloropropane, cis-1,3-dichloropropene, ethyl-t-butyl ether, isopropyl ether, and trans-1,3-dichloropropene) were not detected in any sample, and the maximum detection limits were generally low [less than 1 microgram per cubic meter ($\mu g/m^3$) for four of the five chemicals and 41 $\mu g/m^3$ for the fifth chemical]. The sixth chemical (2-methoxy-2-methyl-butane) was detected in only one sample at a concentration below 1 $\mu g/m^3$ and detection limits were generally low (less than 1 $\mu g/m^3$ and up to 33 $\mu g/m^3$).

As can be seen in Table 1, 65 of the 71 chemicals analyzed were detected in at least one soil gas sample. Only two chemicals (carbon tetrachloride and chloroform) were detected at concentrations exceeding their respective SGSSLs. Chloroform was detected in 100% of the samples at concentrations up to 160,000 $\mu g/m^3$, by far the highest concentration detected in soil gas, with 51 samples exceeding the SGSSL. Carbon tetrachloride was detected in 94% of the samples at concentrations up to 18,000 $\mu g/m^3$, with 3 samples exceeding the SGSSL. Other chemicals detected at concentrations over 1000 $\mu g/m^3$ include tetrachloroethene, TCE, and trichlorofluoromethane.

Finally, no chemical had maximum detection limits greater than their respective SGSSLs; however, the maximum detection limit for four chemicals (1,1,2,2-tetrachloroethane, acrylonitrile, benzyl chloride, and ethylene dibromide) exceeded 10% of their SGSSLs. These chemicals were detected infrequently (1,1,2,2-trichloroethane, acrylonitrile, and benzyl chloride, in 2, 14, and 5 soil gas samples, respectively) at very low concentrations (less than 1 $\mu g/m^3$) or not at all (ethylene dibromide). The majority of the detection limits for these chemicals were also very low (less than 1 $\mu g/m^3$), although some were elevated (up to 42 $\mu g/m^3$ for 1,1,2,2-tetrachloroethane, 46 $\mu g/m^3$ for acrylonitrile, 56 $\mu g/m^3$ for benzyl chloride, and 35 $\mu g/m^3$ for ethylene dibromide) due to sample dilutions.

3.4   Selection of Chemicals of Potential Concern

As described above, 65 of the 71 VOCs analyzed were detected in one or more of the soil gas samples. Of the six chemicals not detected in any sample, five do not have SGSSLs due to the

lack of regulatory toxicity criteria; however, the maximum detection limits for these chemicals were low. The sixth chemical not detected in any soil gas sample, ethylene dibromide, had detection limits that were generally very low and the few elevated detection limits, all below the SGSSL for this chemical, were due to sample dilutions. Exclusion of these six chemicals from the quantitative risk calculations should not affect the overall conclusions of the HRA. Therefore, all 65 chemicals detected in validated soil gas samples were used as the initial list of COPCs, as shown in Table 2. However, to ensure that the risk assessment focuses on those chemicals that contribute the most to the overall risk (U.S. EPA, 1989), a combination of frequency of detection (chemical is detected in less than 5% of the samples) and a toxicity screen were used to further reduce the initial list of potential COPCs based on methods in the approved *HRA Work Plan* (Northgate, 2010a). No chemical was eliminated based solely on frequency of detection.

The chemical toxicity screen used was based on comparison of the maximum detected concentration to a percentage of the SGSSL. To illustrate this SGSSL comparison, Table 2 presents the ratio of the SGSSL divided by the maximum detected soil gas concentration. A ratio >10 indicates that the maximum detected concentration is less than 10% of the SGSSL. A ratio of > 100 indicates that the maximum detected concentration is less than 1% of the SGSSL.

As shown in Table 2, only two chemicals (carbon tetrachloride and chloroform) have maximum detected concentrations greater than their respective SGSSLs (ratios less than 1) and only five additional chemicals (bromodichloromethane, hexachlorobutadiene, naphthalene, tetrachloroethene, and TCE) have maximum detected concentrations greater than 10% of their respective SGSSLs (ratios less than 10). Consistent with the approved *HRA Work Plan* (Northgate, 2010a), these seven chemicals are retained as COPCs.

The remaining detected chemicals generally have very large ratios, indicating that they would not contribute substantially to overall health risk estimates. However, two of these chemicals (benzene and vinyl chloride) are Class A carcinogens, which are normally retained as COPCs regardless of concentration. For purposes of this HRA, benzene is retained as a COPC, but vinyl chloride is not because its ratio of SGSSL to maximum detected concentration was greater than 100 (maximum detected concentration is less than 1% SGSSL).

Finally, one detected chemical (2-methoxy-2-methyl-butane) does not have an SGSSL due to a lack of regulatory toxicity criteria. This chemical was detected in one sample at a concentration less than 1 $\mu g/m^3$ and the detection limits for the remaining samples were also generally below 1 $\mu g/m^3$ and no greater than 33 $\mu g/m^3$. Therefore, exclusion of this chemical from the quantitative risk assessment should not affect the overall conclusions of the HRA.

In summary, based on the toxicity screen evaluation, the following chemicals are identified as COPCs in soil gas and are further evaluated quantitatively in the HRA.

- Benzene

- Bromodichloromethane

- Carbon tetrachloride

- Chloroform

- Hexachlorobutadiene

- Naphthalene

- Tetrachloroethene

- TCE

4.0   EXPOSURE ASSESSMENT

The magnitude of exposure for any given receptor is a function of the amount of the constituent in the exposure medium and the frequency, intensity, and duration of contact with that medium. This section presents the equations and assumptions used to calculate potential exposures for each of the identified COPCs.

4.1   Determination of Representative Exposure-Point Concentrations

A representative exposure-point concentration (EPC) is a COPC-specific and medium-specific concentration used in the dose equation for each receptor and each exposure pathway.   In general, U.S. EPA (1992c) recommends using the 95th upper confidence limit (UCL) of the arithmetic mean concentration for purposes of estimating reasonable maximum or upper-end exposures. However, because one purpose of this HRA is to evaluate potential health risks associated with inhalation of vapors in indoor air, and because it is possible for a building to be constructed over an area represented by a single soil gas sampling location, potential health risks were quantified on a sample-by-sample basis in this HRA. For evaluating potential health risks associated with inhalation of vapors in outdoor air, this may be an overly conservative procedure because it is likely that an outdoor worker would spend time over a wider area than an indoor worker. If a COPC was not detected in a particular sample, one-half the SQL was used. The methods used to estimate indoor and outdoor air concentrations from soil gas measurements are discussed in the following sections.

4.1.1   Indoor Vapors

The migration of COPCs in soil gas from the subsurface and dispersion into indoor air were estimated using the U.S. EPA spreadsheet-based Johnson and Ettinger (J&E) model (U.S. EPA 2004), which is based on the vapor intrusion model published by Johnson and Ettinger (1991). The J&E model incorporates both convective and diffusive mechanisms for estimating the transport of vapors emanating from subsurface media impacted by VOCs into indoor spaces. The major assumption/limitation of the J&E model is that the model is one-dimensional and transport is directed exclusively into the building. That is, vapors only migrate upward from the impacted subsurface media and into the building. Lateral deflection due to the presence of low permeability units or multi-dimensional diffusive transport that reduces the amount of VOC mass that may enter the indoor space is conservatively ignored (diffusion is, physically and mathematically, a three-dimensional process). Additionally, the model assumes that the vapors are at their peak concentration at the floor slab of the building, regardless of the actual depth below ground surface that the highest VOC concentration was detected.

Other assumptions/limitations of the J&E Model are as follows (U.S. EPA, 2004):

- Contaminant vapors enter the structure primarily through cracks and openings in the walls and foundation.

- Convective transport occurs primarily within the building zone of influence and vapor velocities decrease rapidly with increasing distance from the structure.

- Diffusion dominates vapor transport between the source of contamination and the building zone of influence.

- All vapors originating from below the building will enter the building unless the floors and walls are perfect barriers.

- All soil properties in any horizontal plane are homogenous.

- The contaminant is homogeneously distributed within the zone of contamination.

- The areal extent of contamination is greater than that of the building floor in contact with the soil.

- Vapor transport occurs in the absence of convective water movement within the soil column (i.e., evaporation or infiltration), and in the absence of mechanical dispersion.

- The model does not account for transformation processes (e.g., biodegradation, hydrolysis, etc.).

- The soil layer in contact with the structure floor and walls is isotropic with respect to permeability.

- Both the building ventilation rate and the difference in dynamic pressure between the interior of the structure and the soil surface are constant values.

Either site-specific or default soil physical parameters, building characteristics, and exposure assumptions contained in the U.S. EPA J&E model spreadsheet model were used in this evaluation. These values are presented in Table 3. The basis and rationale for the site-specific values are discussed in Appendix E. The chemical properties for the COPCs are the default values coded into the U.S. EPA J&E model spreadsheet as downloaded from the U.S. EPA website (http://www.epa.gov/oswer/riskassessment/airmodel/johnson_ettinger.htm). It should be noted that the U.S. EPA J&E model spreadsheet was designed to evaluate a residential scenario. Under this scenario, a resident is assumed to be present at the site for 24 hours per day; hence, there was no need for U.S. EPA to include an input parameter for exposure time. This is not the case for a commercial scenario in which a worker is assumed to be present at the site for 8 out of 24 hours (U.S. EPA, 2010a; Northgate 2010a). Therefore, for purposes of this HRA, the U.S.

EPA J&E model spreadsheet was adjusted to include an input parameter for exposure time. To ensure conservatism, exposure time was not included for purposes of calculating the SGSSLs.

4.1.2 Outdoor Vapors

The migration of COPCs in soil gas from the subsurface and dispersion into outdoor air was estimated using an approach that is analogous to that used by U.S. EPA (2002) to estimate outdoor air concentrations from chemicals in soil for purposes of calculating soil screening levels (SSLs). Specifically, U.S. EPA calculates a soil-to-air volatilization factor (VF), which relates a soil concentration to an air concentration. The volatilization factor is used to estimate the outdoor air concentration as follows:

$$C_{air-outdoor} = \frac{C_{soil}}{VF}$$

(1)

Where:

$C_{air-outdoor}$ =   outdoor air concentration (mg/m^3)

C_{soil} =   soil concentration (mg/kg)

VF   =   soil-to-air volatilization factor (m^3/kg)

As shown in Equation E-4 of Appendix E of U.S. EPA's guidance document, the VF is based on a dispersion factor (Q/C_{vol}) and a flux rate (J_T) assuming a unit concentration in soil (1 mg/kg or 10^{-6} g/g). This same relationship can be used to estimate the outdoor air concentration from a known soil gas concentration as follows:

$$C_{air-outdoor} = \frac{Flux}{Q/C_{vol}} \times 10^9 \; \mu g/kg$$

(2)

Where:

$C_{air-outdoor}$ =   outdoor air concentration (μg/m^3)

Flux   =   maximum diffusive vapor flux from subsurface soil gas source (g/m^2-sec) [calculated as shown below]

Q/C_{vol} =   Inverse of the ratio of the geometric mean air concentration to the volatilization flux at the center of square source (g/m^2-sec per kg/m^3) [calculated as shown below]

The maximum diffusive vapor flux from subsurface soil gas source from a known soil gas concentration is calculated as follows (ASTM, 2000):

$$Flux = \frac{C_{sg} \times 10^{-6} \ g/\mu g \ \times D^{eff} \ \times \ 10^{-4} \ m^2/cm^2}{L \ \times \ 10^{-2} \ m/cm}$$

(3)

Where:

Flux $\quad = \quad$ maximum diffusive vapor flux from subsurface soil gas source (g/m²-sec)

$C_{sg} \quad = \quad$ concentration in soil gas (μg/m³)

$D^{eff} \quad = \quad$ effective diffusion coefficient (cm²/sec) [calculated as shown below]

L $\quad = \quad$ soil gas sampling depth (cm)

As noted in Section 3.1, the majority of soil gas samples were collected at 5 ft bgs, while a few soil gas samples were collected at 20 ft bgs. For purposes of the HRA, a soil gas sampling depth of 5 ft (150 cm) was assumed for all samples for expediency. This is a health-protective assumption for samples collected at 20 ft bgs.

Equation 1 can be rewritten as follows by substituting Equation 2 for the vapor flux:

$$C_{air-outdoor} = \frac{C_{sg} \times 10^{-6} \ g/\mu g \ \times D^{eff} \ \times \ 10^{-4} \ m^2/cm^2}{L \ \times \ 10^{-2} \ m/cm \ \times \ Q/C_{vol}} \times 10^9 \ \mu g/kg$$

(4)

or

$$C_{air-outdoor} = \ C_{sg} \ \times \ 10^{-6} \ g/\mu g \ \times \left[\frac{D^{eff} \ \times \ 10^{-4} \ m^2/cm^2}{L \ \times \ 10^{-2} \ m/cm \ \times \ Q/C_{vol}} \times 10^9 \ \mu g/kg \right]$$

(5)

where all of the parameters in brackets represent the inverse of a "soil gas-to-air" VF.

The effective diffusion coefficient is calculated on a chemical-specific basis as follows (ASTM 2000, U.S. EPA 2004):

$$D^{eff} = D_a \left(\frac{\theta_a^{3.33}}{n^2} \right) + \left(\frac{D_w}{H'} \right) \times \left(\frac{\theta_w^{3.33}}{n^2} \right)$$

(6)

Where:

D^{eff} = effective diffusion coefficient (cm²/sec)

D_a = diffusivity in air (cm²/sec)

Θ_a = soil air-filled porosity (cm³/cm³)

N = soil total porosity (cm³/cm³)

D_w = diffusivity in water (cm²/sec)

H' = Henry's law constant (dimensionless)

For purposes of this evaluation, the same chemical- and soil-specific assumptions used for estimating indoor air concentrations were used to estimate outdoor air concentrations.

The inverse of the ratio of the geometric mean air concentration to the volatilization flux at the center of square source is calculated as follows (U.S. EPA, 2002):

$$Q/C_{vol} = A \times exp\left[\frac{(\ln A_c - B)^2}{C} \right]$$

(7)

Where:

Q/C_{vol} = Inverse of the ratio of the geometric mean air concentration to the volatilization flux at the center of square source (g/m²-sec per kg/m³)

A = Constant; value for Las Vegas = 13.3093

B = Constant; value for Las Vegas = 19.8387

C = Constant; value for Las Vegas = 230.1652

A_c =   Areal extent of contamination (acres)

As stated previously, potential health risks were estimated on a sample-by-sample basis. The areal extent of contamination was assumed to be 0.5 acre, which is consistent with the approved *HRA Work Plan* for a commercial worker scenario (Northgate 2010a).

4.2   Exposure Calculations

Reasonable maximum exposures to chemicals were calculated for future onsite indoor and outdoor commercial workers using the exposure pathway–specific dose equations presented below and the exposure input parameters presented in Table 4. The J&E model spreadsheet and output sheets for indoor air are included in Appendix F and dose calculation spreadsheets for outdoor air are included in Appendix H. The methodology used to estimate the average daily exposure concentration (EC) via inhalation of vapors in indoor or outdoor air is based on guidance described in U.S. EPA's *Risk Assessment Guidance for Superfund, Volume I: Human Health Evaluation Manual (Part F, Supplemental Guidance for Inhalation Risk Assessment)* (U.S. EPA, 2009). For chemical carcinogens, lifetime average EC estimates are based on chronic lifetime exposure extrapolated over the estimated average 70-year lifetime (U.S. EPA, 1989), to be consistent with cancer unit risk factors, which are based on chronic lifetime exposures. For non-carcinogens, EC estimates are averaged over the estimated exposure period. The equation used to estimate ECs for non-carcinogens (EC_{nc}) and carcinogens (EC_c) is as follows:

$$EC = \frac{C_{air} \times ET \times EF \times ED_w}{AT}$$

where:

EC =   exposure concentration for evaluating exposure to non-carcinogens (EC_{nc}) or carcinogens (EC_c) ($\mu g/m^3$)

C_{air} =   chemical concentration in indoor air ($C_{air\text{-}indoor}$) or outdoor air ($C_{air\text{-}outdoor}$) ($\mu g/m^3$)

ET =   exposure time indoors (ET_i) or outdoors onsite (ET_o) (hr/day)

EF =   exposure frequency indoors (EF_i) or outdoors (EF_o) (days/yr)

ED_w =   exposure duration for commercial workers (year)

AT =   averaging time (hours); equal to the ED × 365 days/year × 24 hours/day for non-carcinogens (AT_{nc}) and 70 years (average lifetime) × 365 days/year × 24 hours/day for carcinogens (AT_c)

5.0   TOXICITY ASSESSMENT

Inhalation unit risk factors (URFs), which are expressed in units of $(\mu g/m^3)^{-1}$, are chemical-specific and experimentally derived potency values that are used to calculate the risk of cancer resulting from exposure to potentially carcinogenic chemicals. The URF is defined as the 95% UCL of the probability of a carcinogenic response per unit daily concentration of a chemical over 70 years. A higher value implies a more potent carcinogenic potential. Non-cancer inhalation reference concentrations (RfCs), which are expressed in units of mg/m^3, are experimentally derived "no-effect" levels that are used to quantify the extent of toxic effects other than cancer due to exposure to chemicals. The RfC is intended to represent the concentration of a chemical that is not expected to cause adverse health effects, assuming daily exposure over a lifetime, even in sensitive individuals, with a substantial margin of safety. With RfCs, a lower value implies a more potent toxicant. These criteria are generally developed by U.S. EPA risk assessment work groups and are listed in the U.S. EPA risk assessment guidance documents and databases.

Table 5 presents the toxicity criteria used in this assessment based on the following hierarchy (based on U.S. EPA, 2003):

1. Integrated Risk Information System (IRIS)
2. U.S. EPA's Provisional Peer Reviewed Toxicity Values (PPRTVs)
3. National Center for Environmental Assessment (NCEA, or other current U.S. EPA sources)
4. Health Effects Assessment Summary Tables (HEAST)
5. U.S. EPA Criteria Documents (e.g., drinking-water criteria documents, drinking-water Health Advisory summaries, ambient water quality criteria documents, and air quality criteria documents)
6. ATSDR toxicological profiles
7. U.S. EPA's Environmental Criteria and Assessment Office (ECAO)
8. Peer-reviewed scientific literature

For carcinogens, the EPA weight-of-evidence classification is identified in the table for each carcinogenic COPC. Originally, EPA used letter designations A through E (U.S.EPA, 1986a). In 1996, EPA proposed replacing the letter designations with narrative descriptions (U.S.EPA, 1996). The information in Table 5 is taken directly from the IRIS database, which contains a mixture of the two classification schemes, depending on when the chemical was last reviewed.

6.0 RISK CHARACTERIZATION

Risk characterization represents the final step in the risk assessment process. In this step, the results of the exposure and toxicity assessments are integrated into quantitative or qualitative estimates of potential health risks. Potential cancer risks and non-cancer adverse health effects are characterized separately. This section also contains a qualitative discussion of the uncertainties associated with this assessment.

6.1 Evaluation of Potential Cancer Risks

Carcinogenic risks are estimated as the incremental probability of an individual developing cancer over a lifetime as a result of exposure to a given chemical at a given concentration. Carcinogenic risks for chemicals in air are evaluated by multiplying the estimated exposure concentration averaged over a lifetime (i.e., EC_c calculated in the exposure assessment) by the chemical's URF. The URF converts the estimated EC_c to incremental risk of an individual developing cancer. According to U.S. EPA (1989), this approach is appropriate for theoretical upper-bound incremental lifetime cancer risks (ILCRs) of less than 1×10^{-2}. Lifetime chemical-specific risks and total Site risks are estimated as follows:

$$Risk_{inhalation} = EC_c \times URF$$

where:

EC_c = exposure concentration for evaluating exposure to carcinogens ($\mu g/m^3$)

URF = unit risk factor ($\mu g/m^3$)$^{-1}$

and

$$Total\ Site\ Risk = \sum Chemical\ Risk$$

The estimated excess cancer risks for each chemical are summed, regardless of the type of cancer associated with each chemical, to estimate the total excess cancer risk for the exposed individual.

For most chemicals, the NDEP point of departure is a cumulative incremental cancer risk of 1×10^{-6} (NDEP, 2009).[2] U.S. EPA considers 1×10^{-6} to 1×10^{-4} to be the target range for

---

[2] There are exceptions to this general rule, including dioxins/furans and asbestos, each of which is evaluated separately from other carcinogenic chemicals (Northgate, 2010a).

acceptable risks at sites where remediation is considered (U.S. EPA, 1990). Estimates of lifetime excess cancer risk associated with exposure to chemicals of less than one-in-one-million (1×10^{-6}) are considered to be so low as to warrant no further investigation or analysis (U.S. EPA, 1990). It should be noted that cancer risks in the 1×10^{-6} to 1×10^{-4} range or higher do not necessarily mean that adverse health effects will be observed. Current methodology for estimating the carcinogenic potential of chemicals is believed to not underestimate the true risk, but could overestimate the true risk by a considerable degree.

6.1.1   Indoor Commercial Worker

The results for the indoor commercial worker are divided into two parts. The first part discusses the results for the entire Tronox facility and adjacent parcels as a whole. The second part discusses the results for different subareas (e.g., remediation zones [RZs] within the Tronox facility and adjacent parcels that have been grouped by geographic areas).

6.1.1.1   Site-Wide Results

The estimated excess cancer risks associated with exposure of an indoor commercial worker to the COPCs in soil gas through inhalation of vapors in indoor air are summarized in Table 6, and the calculation spreadsheets are presented in Appendix F. As stated previously, these values were estimated on a sample-by-sample basis. The estimated total cancer risk for each sample location is also shown on Figure 4, and the data have been contoured to show the areas of the site where the estimated total excess cancer risk is greater than 1×10^{-6} and 1×10^{-5} (no values exceeded 1×10^{-4}).[3] For an indoor commercial worker, the total excess cancer risks due to exposure to chemicals in soil gas range from 2×10^{-9} (SG94, located in RZ-C) to 1×10^{-4} (SG32, also located in RZ-C). Chloroform is the largest contributor to the overall risk (up to >99%) at the majority of locations, with individual chemical risk estimates ranging from 5×10^{-10} to 1×10^{-4}. Carbon tetrachloride is another significant contributor to the overall risk (up to 43%) at some locations, with individual chemical risk estimates ranging from 2×10^{-11} to 3×10^{-6}. None of the other COPCs had overall risk estimates greater than 1×10^{-6}.

The highest estimated total cancer risk estimates shown in Figure 4 are along the western boundary of the Tronox facility and in the middle of the facility, around the Unit buildings, extending to the north. Based on the results of the Phase A and B soil and groundwater

---

[3] The contours were drawn by first entering the excess cancer risk values (in log space) into Surfer and then using the "Natural Neighbors" algorithm with default settings. The "Natural Neighbors" algorithm calculates a weighted average at each location based on nearby values. In some cases, the contours were adjusted manually to more accurately reflect the estimated risk values.

investigations, the primary source of chemicals in soil gas is believed to be shallow groundwater, and the results of this HRA are consistent with that conclusion. The concentrations of chloroform and carbon tetrachloride in shallow groundwater in the vicinity of the Tronox facility are shown in Figures 5 and 6, respectively. These groundwater figures are based on the on-site Phase A/Phase B and compliance data, as well as data for off-site wells obtained from NDEP's regional database. The total risk contours in Figure 4 are similar to the shallow groundwater contours for chloroform, which indicate that there is an off-site chloroform plume extending onto the Tronox facility from the west and an on-site plume extending from the vicinity of the Unit buildings (see Figure 5). With regard to carbon tetrachloride, the highest concentrations in shallow groundwater are also along the western property boundary, which generally corresponds to the soil gas sampling locations with the highest chemical-specific risks for carbon tetrachloride (SG61, SG62, and SG83, all in RZ-C). Finally, although the chemical-specific risks for TCE are relatively low (maximum of 8×10^{-8}), the locations of the highest chemical-specific risk values (SG46 in RZ-A and SG28, SG39, and SG76 in RZ-C) correspond to areas of higher TCE concentrations in shallow groundwater, which are shown in Figure 7. As with Figures 5 and 6, Figure 7 is based on the on-site Phase A/Phase B and compliance data, as well as data for off-site wells obtained from NDEP's regional database.

As stated in Section 3.2.3, some of the soil gas sampling locations were collocated with groundwater sampling locations, and these data were used to further evaluate the relation between chloroform concentrations in soil gas and shallow groundwater. As shown in Table 9, there are a total of 25 pairs of samples in which chloroform was detected in both soil gas and shallow groundwater. These data were plotted and a linear regression model was applied, which showed that the data were reasonable linearly correlated (R^2 of 0.54). However, there are two pairs of samples (SG36/M11 and SG52/MW16) where the soil gas concentration is high, but the shallow groundwater concentration is very low, and these two sets of data points appear to be outliers. When the data were re-analyzed without these samples, the linear correlation was significantly improved (R^2 of 0.94). These data further support the conclusion that the source of chloroform in soil gas is shallow groundwater.

6.1.1.2   Subarea Results

As shown in Table 6, all but one soil gas sampling location has been assigned to an RZ or parcel location group. The designation of the RZ areas was primarily based on soil investigation findings, which may not be the most appropriate basis for designating soil gas exposure areas. Nevertheless, for purposes of this following discussions, the soil gas findings have been subdivided as follows: RZ-A, RZ-B, RZ-C, RZ-D, RZ-E, Parcels A, B, C, D, E, I, and J, and

Parcels F, G, and H. The subarea tables are included in Appendix G and discussed individually below.

Remediation Zone A

There is a total of six soil gas sampling locations in RZ-A. The estimated total excess cancer risks associated with exposure of an indoor commercial worker to the COPCs in soil gas through inhalation of vapors in indoor air range from 1×10^{-8} to 2×10^{-7} (see Table G-1). Chloroform is the largest contributor to the overall risk estimates at five of the six locations (up to 89%), whereas TCE is the largest contributor at the sixth location (SG-47) (43%). This latter result is consistent with the elevated TCE concentrations in shallow groundwater in this area of the site (see Figure 7, groundwater monitoring well M-137). In addition to these six locations within RZ-A, there are nine additional relevant locations within Parcels G and H, and RZ-B that border RZ-A. The total estimated excess cancer risks for these locations are also included in Table G-1. As shown in the table, the overall risks for these adjacent locations range from 2×10^{-9} to 1×10^{-7}, again with chloroform being the largest contributor to the risk estimates at all but one of these locations (up to 92%).

Remediation Zone B

There are a total of 19 soil gas sampling locations in RZ-B. The total estimated excess cancer risks associated with exposure of an indoor commercial worker to the COPCs in soil gas through inhalation of vapors in indoor air range from 5×10^{-9} to 9×10^{-5} (see Table G-2). Chloroform is the largest contributor to the overall risk estimates at all of these locations (up to >99%). As shown in Figure 4, the total excess cancer risk estimates for 5 of the 19 locations (SG-36, SG-40, SG-69 through SG-71) are all located near Unit Buildings 3 and 4 in the east-central portion of RZ-B, with much lower overall risk estimates for locations west, east and south (in Parcel G and RZ-A) of this area. The area of higher estimated risks is consistent with higher chloroform concentrations in shallow groundwater in this area of the site (see Figure 5).

Remediation Zone C

There are a total of 26 soil gas sampling locations in RZ-C. The total estimated excess cancer risks associated with exposure of an indoor commercial worker to the COPCs in soil gas through inhalation of vapors in indoor air range from 2×10^{-9} to 1×10^{-4} (see Table G-3). Chloroform is the largest contributor to the overall risk estimates at all but one of these locations (up to >99%); the one other location, SG94, is located within the Diesel Storage Tank Area (LOU 45), where other

significant contributors to the overall risk estimate include benzene and naphthalene. The total risk estimates for 19 of the 26 locations exceed 1×10^{-6}, and these locations tend to be clustered along the western property boundary and in the east-central portion of the site, areas that coincide with elevated concentrations of chloroform and carbon tetrachloride in shallow groundwater (see Figures 4 through 6).

Remediation Zone D

There are a total of 20 soil gas sampling locations in RZ-D. The total estimated excess cancer risks associated with exposure of an indoor commercial worker to the COPCs in soil gas through inhalation of vapors in indoor air range from 5×10^{-8} to 2×10^{-5} (see Table G-4). Chloroform is the largest contributor to the overall risk estimates at all of these locations (up to >99%). As shown in Figure 4, the total risk estimates for 9 of the 20 locations exceed 1×10^{-6}, and the 7 locations with the highest overall risk estimates are clustered along the western property boundary, which again coincides with elevated concentrations of chloroform in shallow groundwater (see Figure 5).

Remediation Zone E

There are two soil gas sampling locations in RZ-E. The total estimated excess cancer risks associated with exposure of an indoor commercial worker to the COPCs in soil gas through inhalation of vapors in indoor air at both of these locations is 3×10^{-6} (see Table G-5). Chloroform is the largest contributor to the overall risk at both of these locations (96% to 99%), which are located in the east-central portion of the site, coincident with somewhat elevated chloroform concentrations in shallow groundwater (see Figures 4 and 5).

Parcels A through E, I, and J[4]

There are a total of 18 soil gas sampling locations in Parcels A through E, I, and J (5 in Parcel A, 7 in Parcel B, 1 each in Parcels C, D, and E, and 3 in Parcel I; no samples were collected in Parcel J), which are all located north of the main fenced Tronox Facility (see Figure 2). The total estimated excess cancer risks associated with exposure of an indoor commercial worker to the COPCs in soil gas through inhalation of vapors in indoor air at these locations range from 7×10^{-9} to 1×10^{-6} (see Table G-6). Chloroform is the largest contributor to the overall risk estimates at

---

[4] It is noted that a separate screening-level indoor air health risk assessment was conducted for Parcels A/B soil gas data (Northgate, November 15, 2010). Several assumptions related to the indoor air modeling were specific to soil properties in the vicinity of these parcels and risk estimate results are slightly different from those presented in this Site-Wide report. Both sets of calculations result in risk estimates of less than or equal to 1×10^{-6}.

all of these locations (up to >99%). As shown in Figure 4, while none of the total excess cancer risk estimates exceeded 1×10^{-6}, the largest risk estimates are associated with locations in the southeastern portion of this area, which coincides with somewhat elevated chloroform concentrations in shallow groundwater (see Figure 5). In addition to these 18 locations, there are 5 additional relevant locations within RZ-D, which borders Parcel C. The total estimated excess cancer risks for these locations are also shown in Table G-6. As shown in the table, The overall risks for these adjacent locations range from 5×10^{-8} to 3×10^{-6}, again with chloroform being the largest contributor to the risk estimates at all of these locations (up to 98%). The total excess cancer risk estimate exceeds 1×10^{-6} at only one location (SG90), which is near the center of the northern property boundary, directly down-gradient of the off-site chloroform plume (see Figures 4 and 5).

Parcels F, G, and H

There are a total of three soil gas sampling locations in Parcels F, G, and H (one sample in Parcel G and two samples in Parcel H; no samples were collected in Parcel F). All of these parcels are located south of RZ-C, with Parcel F adjacent to the northwest corner of RZ-B, Parcel G west of the southwest corner of RZ-B and northwest corner of RZ-A, and Parcel H south of RZ-A (see Figure 2). The total estimated excess cancer risks associated with exposure of an indoor commercial worker to the COPCs in soil gas through inhalation of vapors in indoor air at these locations range from 2×10^{-9} to 3×10^{-8} (see Table G-7). Chloroform is the primary contributor to the overall risk estimate for the sample in Parcel G (SG45) (86%), whereas chloroform, benzene and naphthalene are the primary contributors to the overall risk estimates for the samples in Parcel H (on the order of 25% to 40% depending on the chemical and sample). In addition to these three locations within Parcels G and H, there are nine additional relevant locations within RZ-A, RZ-B, and RZ-C that border all three of these parcels. The total estimated excess cancer risks for these locations are also included in Table G-7. As shown in the table, the overall risks for these adjacent locations range from 5×10^{-9} to 6×10^{-5}, with chloroform being the primary contributor to the risk estimates at all but one of these locations (up to 99%). As shown in Figure 4, the total excess cancer risk estimate exceeds 1×10^{-6} at only one location (SG61), which is in RZ-C, along the western property boundary north of Parcel F, within the off-site chloroform plume (see Figure 5). For the remaining locations, including all those in the vicinity of Parcels G and H, the highest overall risk estimate was 4×10^{-7}.

6.1.2 Outdoor Commercial Worker

The estimated excess cancer risks associated with exposure of an outdoor commercial worker to the COPCs in soil gas through inhalation of vapors in outdoor air are summarized in Table 7, and the calculation spreadsheets are presented in Appendix H. These calculations are limited to those COPCs for which estimated exposure to indoor air exceed an excess cancer risk of 1×10^{-6} or hazard index of 1 (i.e., carbon tetrachloride and chloroform), because modeled outdoor air concentrations are orders of magnitude lower than modeled indoor air concentrations. For an outdoor commercial worker, the total excess cancer risks due to exposure to chemicals in soil gas range from 5×10^{-12} to 1×10^{-6}, with chloroform being the largest contributor to the overall risk estimates. These values are equal to or below the lower end of the generally acceptable risk range, indicating that potential exposure to COPCs in soil gas through inhalation of vapors by an outdoor commercial worker should not pose an unacceptable carcinogenic health risk under the conditions evaluated.

6.2   Evaluation of Non-Cancer Health Effects

Non-cancer adverse health effects are evaluated by comparing the estimated exposure concentration (i.e., EC_{nc} estimated in the exposure assessment) with an exposure level at which no adverse health effects are expected to occur for a long period of exposure (i.e., RfC). The EC_{nc} and RfC are compared by dividing the EC_{nc} by the RfC to obtain the EC_{nc}/RfC ratio, as follows:

$$Hazard\ Quotient_{inhalation} = \frac{EC_{nc} \times 10^{-3}\ mg/\mu g}{RfC}$$

where:

  EC_{nc} = exposure concentration for evaluating exposure to non-carcinogens ($\mu g/m^3$)

  RfC = reference concentration (mg/m^3)

A hazard quotient less than or equal to 1 indicates that the predicted exposure to that chemical should not result in an adverse non-carcinogenic health effect (U.S. EPA, 1989). If more than one chemical is evaluated, the hazard quotients for all COPCs are summed to determine whether exposure to a combination of chemicals poses a health concern. This sum of the hazard quotients is known as a Hazard Index (HI).

$$Hazard\ Index = \sum Hazard\ Quotients$$

The NDEP non-cancer risk management target is a HI value of less than or equal to 1 (NDEP, 2009a). It should be noted that HI or HQ values greater than 1 do not necessarily mean that adverse health effects will be observed, because a substantial margin of safety has been incorporated into many of the RfCs.

6.2.1   Indoor Commercial Worker

The estimated non-cancer hazard quotients and hazard indices associated with exposure of an indoor commercial worker to the COPCs in soil gas through inhalation of vapors in indoor air are summarized in Table 8, and the calculation spreadsheets are presented in Appendix F. As stated previously, these values were estimated on a sample-by-sample basis. The total hazard indices for an indoor commercial worker due to exposure to chemicals in soil gas range from 0.00001 to 0.1. All of these values are well below 1, indicating that potential exposure to COPCs in soil gas through inhalation of indoor air by an indoor commercial worker should not pose a potential non-carcinogenic health risk under the conditions evaluated. Chloroform is the largest contributor to the overall hazard index at most sampling locations. Other significant contributors to the overall hazard index at some locations include carbon tetrachloride, naphthalene, and tetrachloroethene.

6.2.2   Outdoor Commercial Worker

The estimated non-cancer hazard quotients and hazard indices associated with exposure of an outdoor commercial worker to the COPCs in soil gas through inhalation of vapors in outdoor air are summarized in Table 7, and the calculation spreadsheets are presented in Appendix H. As stated previously, these calculations were limited to carbon tetrachloride and chloroform. For an outdoor commercial worker, the total hazard indices due to exposure to chemicals in soil gas range from 7×10^{-9} to 0.001, with chloroform contributing nearly 100% of the total hazard index. These values are well below 1, indicating that potential exposure to COPCs in soil gas through inhalation of vapors by an outdoor commercial worker should not pose an unacceptable non-carcinogenic health risk under the conditions evaluated.

6.3   Uncertainty Analysis

Uncertainty is inherent in many aspects of the risk assessment process. Uncertainty generally arises from a lack of knowledge as well as variability of (1) site conditions and future site use; (2) toxicity and dose-response of the COPCs; and/or (3) the extent to which an individual may be

exposed (if at all) to the chemicals. This lack of knowledge means that assumptions must be made based on information presented in the scientific literature or on professional judgment. Although some assumptions have significant scientific basis, many do not. The assumptions that introduce the greatest amount of uncertainty, and their effects on the findings of this HRA, are summarized in Table 10, and discussed further below. This discussion is qualitative in nature, reflecting the difficulty in quantifying the uncertainty in specific assumptions. In general, assumptions were selected in a manner that purposely biases the process toward health protection.

6.3.1   Uncertainty Associated with Site Characterization Data

Soil gas samples were collected from 95 locations across the 450-acre Tronox facility and adjacent parcels. As presented in Table 1 of the Soil Gas Work Plan (ENSR, 2008a), the majority of sampling locations were located within one of the 18 LOUs identified as being potential sources of VOCs or in areas where VOCs had been detected in soil or groundwater, and the remaining soil gas sample locations were placed in other areas of the Site. As also noted in Table 1 of the Soil Gas Work Plan, the majority of the sample locations were targeted to evaluate LOUs, off-site groundwater and on-site groundwater as potential sources, and some samples were also targeted to evaluate vapor intrusion into existing buildings. All soil gas samples were analyzed for a full suite of VOCs. Because most of the soil gas sampling locations were targeted, and samples from these locations were analyzed for chemicals associated with historical operations, the relative uncertainty in the site characterization data is considered to be low.

6.3.2   Uncertainty Associated with Data Usability/Data Evaluation

All of the soil gas data were evaluated in a single DVSR. As discussed in Section 3.2, a small number of data points (6% of the total analytical dataset) were found to be qualified based on minor method blank, field duplicate, and quantitation issues but were deemed acceptable and were not biased low. All results for a single sample were rejected based on helium tracer concentrations and this sample was successfully replaced by a second sample collected at this location.   Accordingly, with the exception of the single sample for which data were rejected, all soil gas data were deemed to be usable for risk assessment.

6.3.3   Uncertainty Associated with Selection of COPCs

At total of 65 chemicals were detected in at least one soil gas sample and were included in the COPC selection process. Of these 65 chemicals, 8 were identified as COPCs. For those

chemicals that were not selected as COPCs, the maximum detected concentration was generally a factor of 10, if not a factor of 100 or more, lower than the SGSSL; therefore, exclusion of these chemicals from the quantitative risk assessment may slightly underestimate the potential health risks posed by the Site, but to such a small degree as to be inconsequential to the overall results of the HRA.

6.3.4   *Uncertainty Associated with Exposure-Point Concentrations*

Estimated excess cancer risks and non-cancer hazard indices were calculated on a sample-by-sample basis because it is possible for a building to be constructed over an area represented by a single soil gas sampling location. This approach may over- or underestimate the risk estimates depending on the representativeness of a single sample for an entire building footprint. Furthermore, this may be an overly conservative procedure for purposes of estimating potential health risks associated with inhalation of vapors in outdoor air, because it is likely that an outdoor worker would be spend time over a wider area than an indoor worker.

6.3.5   *Uncertainty Associated with Fate-and-Transport Modeling*

Fate-and-transport models were used in this HRA to estimate indoor air and outdoor air concentrations from measured soil gas concentrations. For indoor air, the U.S. EPA J&E model spreadsheet was used. As discussed in Section 4.1.1, the J&E model has numerous assumptions and limitations, each of which may over- or underestimate the predicted indoor air concentration. In this case, site-specific soil physical parameters were used in the modeling, which should reduce the uncertainty in the model estimates. For outdoor air, an approach analogous to that used by U.S. EPA to estimate outdoor air concentrations from chemicals in soil was used. This model also has assumptions that may over- or underestimate the predicted concentrations. Two specific areas of uncertainty in the indoor air modeling are further discussed below.

6.3.5.1   *Air Exchange Rate and Vapor Flow Rate in Commercial Buildings*

There is relatively little guidance on appropriate values for the air exchange rate and vapor flow rate into commercial buildings. As discussed in Appendix E, U.S. EPA recommends a value of 0.25 per hour (0.25/hr) for the air exchange rate for a residential building, but does not provide a recommended value for a commercial building, in their J&E Model User's Guide (U.S. EPA, 2004). The California Environmental Protection Agency (Cal-EPA) recommends a value of 1/hr for commercial buildings (Cal-EPA 2005), whereas the Michigan Department of Environmental Quality (MDEQ) recommends a value of 2/hr (Michigan Environmental Science Board 2001). For purposes of this HRA, the more conservative (i.e., health-protective) value of 1/hr was used.

With regard to the vapor flow rate into a building (Q_{soil}), this value can be calculated based on various site-specific or default values related to soil vapor permeability, pressure differentials, and size of cracks. However, because a wide range of values can be predicted, U.S. EPA provides a recommended "default" value for residential buildings (5 L/m) based on empirical data, but does not provide a recommendation for commercial buildings (U.S. EPA, 2004). Cal-EPA recommends scaling the default residential value based on the size of the commercial building (e.g., if the commercial building is twice the size as the default residential building, then the Q_{soil} value is doubled) rather than allowing the model to calculate this value (Cal-EPA 2005). For purposes of this HRA, the scaled Q_{soil} value (4×5 L/m or 20 L/m because the default commercial building size described above is 4-times the default residential building size) was conservatively used.

To assess the uncertainty in using these assumptions, the estimated excess cancer risks and non-cancer hazard indices were re-calculated using less conservative, but still reasonable, values for these parameters (i.e., an air exchange rate of 2/hr based on MDEQ guidance and a calculated Q_{soil} based on site-specific assumptions as originally conceived in the J&E model). The calculation spreadsheets and model output are provided in Appendix F, and the results are shown on Figure 8. The resulting estimates are approximately a factor of four lower (i.e., on a site-wide basis, excess cancer risks range from 6×10^{-10} to 3×10^{-5}), and although there are still areas of the Site where the estimated risks exceed 1×10^{-6}, the extent of that area is substantially smaller.

6.3.5.2 *Indoor Air Quality Study*

In part to assess the uncertainty in the indoor air vapor intrusion exposure pathway, an indoor air quality (IAQ) study has been initiated at the Tronox facility. The first round of indoor and outdoor air samples were collected at several locations throughout the facility in May 2010 (Northgate, 2010b), and analyzed for chloroform, carbon tetrachloride, and TCE. Chloroform and carbon tetrachloride were detected in all but one indoor air sample and all outdoor air samples. TCE was detected in all indoor air samples and some of the outdoor air samples; however, the detection limits in the outdoor samples were elevated due to sampling conditions (Northgate, 2010b). Preliminarily, the measured chloroform and carbon tetrachloride concentrations were lower than that predicted by the J&E model, whereas the measured TCE concentrations were higher than that predicted by the J&E model. A second round of indoor and outdoor air sampling, which is scheduled for December 2010, will provide additional information.

6.3.6 Uncertainty Associated with Exposure Assessment

The exposure assessment in this HRA is based on a reasonable maximum exposure (RME) scenario, which is defined by EPA as the highest exposure that could reasonably be expected to occur for a given exposure pathway at a site (U.S. EPA, 1989). To achieve this goal, the RME scenario uses highly conservative exposure assumptions. For example, this HRA assumes that a future onsite commercial worker is present at the site 225 days (outdoor worker) or 250 days (indoor worker) per year, for 25 years. These upper-bound, default estimates of exposure most likely overestimate the potential health risks associated with the Site. It should be noted, however, that the HRA was limited to inhalation of vapors in indoor or outdoor air. The potential health risks associated with direct contact with chemicals in soil will be addressed separately for each RZ and the parcels. Finally, it should be noted that potential health risks associated with inhalation of vapors in outdoor air were not evaluated quantitatively for off-Site receptors. However, because (1) off-Site receptors would be exposed to lower concentrations than on-Site receptors; and (2) the estimated health risks for on-Site receptors are below levels of concern, potential health risks to off-Site receptors would also be below levels of concern.

6.3.7 Uncertainty Associated with Toxicity Assessment

One of the largest sources of uncertainty in any risk assessment is the limited understanding of toxicity to humans who are exposed to the low concentrations that are generally encountered in the environment. The majority of the available toxicity data are from animal studies; these data are extrapolated using mathematical models or multiple uncertainty factors to predict what might occur in humans. Sources of conservatism in the toxicity criteria used in this HRA include:

- The use of conservative methods and assumptions to extrapolate from high-dose animal studies to predict the possible response in humans at exposure levels far below those administered to animals;

- The assumption that chemicals considered to be carcinogens do not have thresholds (i.e., for all doses greater than zero, some risk is assumed to be present); and

- The fact that epidemiological studies (i.e., human exposure studies) are limited and are not generally considered in a quantitative manner in deriving toxicity values.

In aggregate, these assumptions lead to overestimates of risk, such that the actual risk is unlikely to be higher than the estimated risk, but could be considerably lower. Chemical-specific uncertainties in toxicity criteria are provided below for chemicals that contribute most to the

estimated cancer risks (carbon tetrachloride and chloroform) and HIs (carbon tetrachloride, chloroform, naphthalene, and tetrachloroethene), followed by a discussion regarding chemicals for which surrogate criteria were used, or no criteria were available.

Carbon Tetrachloride

The URF for carbon tetrachloride is based on increased incidence of pheochromocytoma in treated male mice observed in a 2-year chronic inhalation study (U.S. EPA, 2010b). With regard to their confidence in this criterion, U.S. EPA comments that although pheochromocytomas were observed in only one species, the available experimental evidence supports a conclusion that mouse pheochromocytomas are relevant to humans. Further, because there is no information on the mode of action (MOA) for this tumor, the URF is based on a linear low-dose extrapolation approach. Information on the MOA to inform this approach would significantly reduce the uncertainty in this URF (U.S. EPA, 2010b).

The RfC for carbon tetrachloride is based on a chronic 2-year inhalation toxicity study in rats. The critical effect is fatty changes in the liver. The U.S. EPA applied an uncertainty factor of 100 (a factor of 10 for intraspecies differences, a factor of 3 for interspecies extrapolation, and a factor of 3 for database deficiencies) to the $BMCL_{10 [HEC]}$ [Benchmark concentration representing the lower bound on the response in 10% of the population, adjusted to a human equivalent concentration using a physiologically-based pharmacokinetic (PBPK) model]. U.S. EPA concludes that the overall confidence in the RfC is medium because confidence in the principal animal study is high and confidence in the overall database is medium (lack of an adequate inhalation multigenerational study of reproductive function) (U.S. EPA, 2010b)

Chloroform

The URF for chloroform is based on increased hepatocellular carcinoma in treated female mice observed in a chronic 78-week oral gavage study. With regard to their confidence in this criterion, U.S. EPA comments that an adequate number of animals were treated and observed, and risk estimates derived from mice or rat kidney data are generally supportive of the URF (U.S. EPA, 2010b).

The RfC for chloroform is based on a 1- to 4-year study of workers occupationally exposed to chloroform in a pharmaceutical plant (ATSDR, 1997a). The critical effect is hepatomegaly, which was found in 25% of the chloroform-exposed workers. The Agency for Toxic Substances Disease Registry (ATSDR) applied an uncertainty factor of 100 (a factor of 10 for intraspecies differences and a factor of 10 to extrapolate from a low adverse effect level [LOAEL] to a no

adverse effect level [NOAEL]) to the LOAEL. ATSDR does not comment on their confidence in this value.

Naphthalene

The RfC for naphthalene is based on a 2-year chronic inhalation study in mice (U.S. EPA 2010b). Nasal effects, including hyperplasia and metaplasia were observed in the respiratory and olfactory epithelium, respectively, of treated animals. U.S. EPA applied an uncertainty factor of 3000 (a factor of 10 for intraspecies differences, a factor of 10 for interspecies differences, a factor of 10 to extrapolate from a LOAEL to a NOAEL, and a factor of 3 for database deficiencies) to the LOAEL converted to a human equivalent concentration (HEC). U.S. EPA concludes that the overall confidence in the RfC is low to medium because confidence in the principal study is medium (adequate number of animals, but high mortality), and confidence in the overall database is low to medium (lack of subchronic or chronic studies in other animal species and no reproductive or developmental studies for inhalation exposure) (U.S. EPA, 2010b).

Tetrachloroethene

The RfC for tetrachloroethene is based on a study of women occupationally exposed to tetrachloroethene for an average of ~10 years in dry cleaning shops (ATSDR, 1997b). The critical effect was increased reaction times in a series of neurobehavioral tests. The ATSDR applied an uncertainty factor of 100 (a factor of 10 for intraspecies differences and a factor of 10 to extrapolate from a LOAEL to a NOAEL) to the LOAEL converted from occupational exposure to continuous exposure (i.e., 8/24 hours and 5/7 days). ATSDR cites several other studies in support of their analysis, but otherwise does not comment on their confidence in this value.

Surrogate Criteria and Missing Criteria

Surrogate toxicity criteria were used for the following chemicals as directed by NDEP (2010b):

Chemical	Surrogate
1,2-Dichlorotetrafluoroethane	1,1,2-Trichloro-1,2,2-trifluoroethane
1,3-Dichlorobenzene	1,2-Dichlorobenzene
4-Ethyltoluene	Isopropylbenzene (cumene)

4-Isopropyltoluene	Isopropylbenzene (cumene)
alpha-Methylstyrene	Styrene
cis-1,2-Dichloroethene	trans-1,2-Dichloroethene
n-Butylbenzene	Isopropylbenzene (cumene)
n-Octane	C5-C8 alkanes and cylcoalkanes
sec-Butylbenzene	Isopropylbenzene (cumene)
t-Butyl alcohol	sec-Butyl alcohol
tert-Butylbenzene	Isopropylbenzene (cumene)

None of these chemicals were identified as COPCs; therefore, use of these surrogate toxicity criteria does not affect the conclusion of this HRA.

Finally, one detected chemical (2-methoxy-2-methyl-butane) does not have a regulatory toxicity criterion or other recommended value. As stated in Section 3.4, this chemical was detected in one sample at a concentration less than 1 μg/m^3 and the detection limits for the remaining samples were also generally below 1 μg/m^3 and no greater than 33 μg/m^3. Therefore, exclusion of this chemical from the quantitative risk assessment should not affect the overall conclusions of the HRA.

6.3.8   Uncertainty Associated with Risk Characterization

The uncertainties associated with risk characterization are generally the result of the combined uncertainties in the site conditions, exposure assumptions, and toxicity criteria. In this HRA, potential health risks were quantified for future onsite commercial workers associated with exposure to chemicals in soil gas through inhalation of vapors in indoor or outdoor air. Given the highly conservative nature of the exposure parameters used to characterize this pathway, especially for the RME scenario, it is highly unlikely that the same receptor would be exposed at that level over the entire duration of exposure. These conservative estimates of exposure were then combined with even more conservative estimates of acceptable exposure (RfC) or carcinogenic potency (URF) to estimate the magnitude (non-cancer) or likelihood (cancer) of potential effects.

One source of uncertainty that is unique to risk characterization is the assumption that the total risk associated with exposure to multiple chemicals is equal to the sum of the individual risks for each chemical (i.e., the risks are additive). Other possible interactions include synergism, where

the total risk is higher than the sum of the individual risks, and antagonism, where the total risk is lower than the sum of the individual risks. Relatively few data are available regarding potential chemical interactions following environmental exposure to chemical mixtures. Some studies have been carried out in rodents that were given simultaneous doses of multiple chemicals. The results of these studies indicated that no interactive effects were observed for mixtures of chemicals that affect different target organs (i.e., each chemical acted independently), whereas antagonism was observed for mixtures of chemicals that affect the same target organ, but by different mechanisms (Risk Commission, 1997).

While there are no data on chemical interactions in humans exposed to chemical mixtures at the dose levels typically observed in environmental exposures, animal studies suggest that synergistic effects will not occur at levels of exposure below their individual effect levels (Seed et al., 1995). As exposure levels approach the individual effect levels, a variety of interactions may occur, including additive, synergistic, and antagonistic interactions (Seed et al., 1995).

EPA guidance for risk assessment of chemical mixtures (U.S. EPA, 1986b) recommends assuming an additive effect following exposure to multiple chemicals. Subsequent recommendations by other parties, such as the National Research Council (1988) and the Presidential/Congressional Commission on Risk Assessment and Risk Management (Risk Commission, 1997) have also advocated a default assumption of additivity. As currently practiced, risk assessments of chemical mixtures generally sum cancer risks regardless of tumor type, and sum non-cancer hazard indices regardless of toxic endpoint or mode of action. Given the available experimental data, this approach likely overestimates potential risks associated with simultaneous exposure to multiple chemicals.

In summary, these and other assumptions contribute to the overall uncertainty in the results of the HRA. However, given that the largest sources of uncertainty generally result in overestimates of exposure or risk, it is believed that the non-carcinogenic and carcinogenic risks presented in this HRA represent conservative estimates of the risks, if any, posed by residual chemicals in soil gas at the site.

6.4   Data Quality Assessment

Data quality assessment (DQA) is an analysis that is performed after the risk assessment to determine whether enough data have been collected to support the risk-based decisions that are being supported by the risk assessment. Sample-size calculations were conducted for carbon tetrachloride, naphthalene, and tetrachloroethene. The formula used for calculation of sample

size is based on a non-parametric test (the Wilcoxon signed rank test), and on simulation studies performed by Pacific Northwest National Laboratories (PNNL, 2001). Essentially, the formula is the one that would be used if a normal-based test (such as a standard t-test) were being performed, but an adjustment is made (multiplier of 1.16) to account for the intent to perform a non-parametric test. The formula is as follows:

$$n = 1.16 \left[\frac{s^2}{\Delta^2} (z_{1-\alpha} + z_{1-\beta(\mu)})^2 + 0.5 z_{1-\alpha}^2 \right]$$

where:

n	=	number of samples
s	=	estimated standard deviation of concentrations/fibers
Δ	=	width of the gray region (the difference between the threshold value stated in the null hypothesis and the point at which β is specified)
α	=	significance level or Type I error tolerance
$\beta(\mu)$	=	Type II error tolerance
z	=	quantile from the standard normal distribution

For each chemical, inputs for the calculations include an estimate of the variance from the measured data, a desired significance level, and desired power of the test. The power of the test must be specified at a concentration of interest (which determines the tolerable difference from the threshold value), based on the SGSSLs. The calculations provided in Table 10 cover a range of significance (α) and power (1-β) levels, including the most commonly used 0.05 significance level and 80% power. Table 11 shows the minimum sample size necessary to detect a 10%, 20% or 30% difference from the threshold value for each combination of significance and power level.

As shown in Table 11, there is sufficient sample size for naphthalene and tetrachloroethene to detect a 10% difference at a 0.05 significance level with 85% power (1-β). The same conclusion can be drawn for carbon tetrachloride, except with 75% power; the available sample size (n=95) exceeds the necessary sample size for all other parameters. It should be noted that chloroform, which is the primary contributor to overall risks at the majority of sampling locations, was not included in the DQA because the measured soil gas concentrations were well in excess of the SGSSL at multiple locations and the extreme variability in detected concentrations skews this

type of analysis. Nevertheless, the 95 soil gas sample locations are considered sufficient support the results of this HRA because the primary source of chloroform in soil gas is believed to be shallow groundwater and the distribution of chloroform in shallow groundwater has been delineated.

7.0   CONCLUSIONS

The objective of the site-wide soil gas HRA was to evaluate the potential for adverse health impacts that may occur as a result of potential exposure to chemicals in soil gas via inhalation of vapors in indoor or outdoor air.

Soil gas data collected as part of the Phase B Source Area Investigation Soil Gas Survey were evaluated and considered useable for purposes of this HRA. All data were reviewed and data usability requirements were met for purposes of conducting the HRA. COPCs were selected according to a multi-step process, including a toxicity screen, frequency of detection, and CSM considerations. Based on this process, eight chemicals (benzene, bromodichloromethane, carbon tetrachloride, chloroform, hexachlorobutadiene, naphthalene, tetrachloroethene, and TCE) were selected as COPCs. Cumulative cancer risks and hazard index values were estimated on a sample-by-sample basis and 1×10^{-6} and 1×10^{-5} risk isopleths were generated (no total excess cancer risk estimates exceeded 1×10^{-4}). The results of the HRA can be summarized as follows:

Site –Wide Findings

- For an indoor commercial worker, the excess cancer risks due to exposure to chemicals in soil gas range from 2×10^{-9} (SG94, located in RZ-C) to 1×10^{-4} (SG32, also located in RZ-C). Chloroform is the largest contributor to the overall risk (up to >99%) at the majority of locations, with individual chemical risk estimates ranging from 5×10^{-10} to 1×10^{-4}. Carbon tetrachloride is another significant contributor to the overall risk (up to 43%) at some locations, with individual chemical risk estimates ranging from 2×10^{-11} to 3×10^{-6}. None of the other COPCs had overall risk estimates greater than 1×10^{-6}.

- The estimated non-cancer hazard quotients and hazard indices associated with exposure of an indoor commercial worker to the COPCs in soil gas through inhalation of vapors in indoor air range from 0.00001 to 0.1. All of these values are well below 1, indicating that potential exposure to COPCs in soil gas through inhalation of vapors by an indoor commercial worker should not pose an unacceptable non-carcinogenic health risk under the conditions evaluated.. Chloroform is the largest contributor to the overall hazard index at most sampling locations. Other significant contributors to the overall hazard index at some locations include carbon tetrachloride, naphthalene, and tetrachloroethene.

- The estimated excess cancer risks associated with exposure of an outdoor commercial worker to the COPCs in soil gas through inhalation of vapors in outdoor air range from 5×10^{-12} to 1×10^{-6} and the non-cancer hazard indices range from 7×10^{-9} to 0.001. These values indicate that potential exposure to COPCs in soil gas through inhalation of vapors

by an outdoor commercial worker should not pose an unacceptable carcinogenic or non-carcinogenic health risk under the conditions evaluated. Chloroform was the largest contributor to the overall excess cancer risks and non-cancer hazard indices.

Area-Specific Findings

The designation of the RZs was primarily based on soil investigation findings, which may not be the most appropriate basis for designating soil gas exposure areas. Nevertheless, risk estimates were provided for RZ-A through RZ-E as well as the adjacent parcels.

- For RZ-A and all the parcels, the estimated excess cancer risks associated with exposure of an indoor commercial worker to the COPCs in soil gas through inhalation of vapors in indoor air are at or below 1×10^{-6} and hazard index values are well below 1.
- For RZ-B, the estimated excess cancer risks associated with exposure of an indoor commercial worker to the COPCs in soil gas through inhalation of vapors in indoor air range from 5×10^{-9} to 9×10^{-5}, with the highest risk estimates near Unit Buildings 3 and 4 in the east-central portion of RZ-B. The area of higher estimated risks is consistent with higher chloroform concentrations in shallow groundwater in this area of the site.
- For RZ-C, the estimated excess cancer risks associated with exposure of an indoor commercial worker to the COPCs in soil gas through inhalation of vapors in indoor air range from 2×10^{-9} to 1×10^{-4}, with the highest risk estimates clustered along the western property boundary and in the east-central portion of the site, areas that coincide with elevated concentrations of chloroform and carbon tetrachloride in shallow groundwater.
- For RZ-D, the estimated excess cancer risks associated with exposure of an indoor commercial worker to the COPCs in soil gas through inhalation of vapors in indoor air range from 5×10^{-8} to 2×10^{-5}, with the highest risk estimates clustered along the western property boundary, which again coincides with elevated concentrations of chloroform in shallow groundwater.
- For RZ-E, there are only two soil gas sampling locations and the total excess cancer risks associated with exposure of an indoor commercial worker to the COPCs in soil gas through inhalation of vapors in indoor air at both of these locations is 3×10^{-6}.

There are multiple sources of uncertainty associated with the HRA results, particularly regarding model predictions of indoor air concentrations as a result of vapor intrusion. Site-specific data were used when possible to reduce uncertainty. There is relatively little guidance on appropriate values for two parameters, i.e., air exchange rate and vapor flow rate into commercial buildings.

The above results are based on conservative (i.e., heath-protective) assumptions for these two parameters. If less conservative, but still reasonable, assumptions are used, the estimated excess cancer risks and non-cancer hazard indices are a factor of four lower (i.e., on a site-wide basis, excess cancer risks range from 6×10^{-10} to 3×10^{-5}). Although there are still areas of the Site where the estimated risks exceed 1×10^{-6}, the size of those areas is substantially smaller when more reasonable assumptions are incorporated.

Carbon tetrachloride, naphthalene, and tetrachloroethene were included in the DQA, which indicates that a sufficient number of soil gas samples were collected to support the results of this HRA.   Chloroform was not included in the DQA; however, the 95 soil gas sample locations are considered sufficient because the primary source of chloroform in soil gas is believed to be shallow groundwater and the distribution of chloroform in shallow groundwater has been delineated. Findings from this site-wide soil gas HRA will be incorporated into the RZ and parcel-specific risk assessments, as appropriate, to allow for risk management decisions.

8.0 REFERENCES

AECOM, Inc. (AECOM). 2008. *Revised Phase B Site Investigation Work Plan for Areas I, II, III and IV, Text, Tables and Figures.* Tronox LLC Facility. Henderson, Nevada. December 2008.

American Society for Testing and Materials (ASTM). 2000. Standard Guide for Risk-Based Corrective Action. E2081-00.

Agency for Toxic Substances Disease Registry (ATSDR). 1997a. Toxicological Profile for Chloroform.

Agency for Toxic Substances Disease Registry (ATSDR). 1997b. Toxicological Profile for Tetrachloroethene.

California Environmental Protection Agency (Cal-EPA). 2005. Guidance for the Evaluation and Mitigation of Subsurface Vapor Intrusion to Indoor Air. California Environmental Protection Agency, Department of Toxic Substances Control, Sacramento, CA.

Ecology and Environment. 1982. Summary and Interpretation of Environmental Quality Data, BMI Industrial Complex, Henderson, Nevada. November.

ENSR Corporation (ENSR). 2005. Conceptual Site Model (CSM). Kerr-McGee Facility, Henderson, Nevada. February.

ENSR Corporation (ENSR) 2007, Phase A Source Area Investigation Results Report, Tronox LLC Facility, Henderson, Nevada, September.

ENSR Corporation (ENSR). 2008a. Phase B Source Area Investigation Work Plan – Soil Gas Survey. Tronox LLC Facility, Henderson, Nevada. March.

ENSR Corporation (ENSR). 2008b. Revised Draft Data Validation Summary Report, Phase B Source Area Investigation Soil Gas Survey, Tronox LLC Facility, Henderson, Nevada, October.

ENSR Corporation (ENSR). 2008c. Quality Assurance Project Plan, Tronox LLC Facility, Henderson, Nevada.

ERM and MWH. 2007. Basic Remediation Company (BRC) Field Sampling and Standard Operating Procedures, BMI Common Areas. August.

Hargis + Associates. 2008. Technical Memorandum, 2007 Vapor Intrusion Groundwater Monitoring Results. February.

Interstate Technology Regulatory Council (ITRC). 2007. Technical and Regulatory Guidance – Vapor Intrusion Pathway: A Practical Guideline.

Johnson, P.C., and R.A. Ettinger. 1991. Heuristic model for predicting the intrusion rate of contaminant vapors in buildings. Environ. Sci. Technol. 25:1445-1452.

Michigan Environmental Science Board. 2001. Evaluation of the Michigan Department of Environmental Quality's Generic Groundwater and Soil Volatilization to Indoor Air Inhalation Criteria. (A Science Report to Governor John Engler). Michigan Environmental Science Board, Lansing, MI.

Nevada Division of Environmental Protection (NDEP). 1996. Nevada Administrative Code Chapter NAC 445A. Adopted Permanent Regulation of the Nevada State Environmental Commission. LCB File No. R119-96.

Nevada Division of Environmental Protection (NDEP). 2006. Guidance on Data Validation, BMI Plant sites and Common Areas Projects, Henderson, Nevada.

Nevada Division of Environmental Protection (NDEP). 2008a. *BMI Plant Sites and Common Areas Projects, Henderson, Nevada: Statistical Analysis Recommendations for Field Duplicates and Field Splits.* Bureau of Corrective Actions, Special Projects Branch, 2030 East Flamingo Rd, Suite 230, Las Vegas, NV 89119. November 14.

Nevada Division of Environmental Protection (NDEP). 2008b. Guidance on the Development of Summary Statistic Tables at the BMI Complex and Common Areas in Henderson, Nevada. Bureau of Corrective Actions, Special Projects Branch, 2030 East Flamingo Rd, Suite 230, Las Vegas, NV 89119. December 10.

Nevada Division of Environmental Protection (NDEP). 2009. User's Guide and Background Technical Document for Nevada Division of Environmental Protection (NDEP) Basic Comparison Levels (BCLs) for Human Health for the BMI Complex and Common Areas. Revision 4-November.

Nevada Division of Environmental Protection (NDEP). 2010a. September 2010 Revised Data Usability Guidance, BMI Plant Sites and Common Areas Projects, Henderson, Nevada. September 1.

Nevada Division of Environmental Protection (NDEP). 2010b. Letter to Mr. Matt Paque, Tronox LLC, from Ms. Shannon Harbour, regarding NDEP Response to: *Revised Technical Memorandum: Screening-Level Indoor Air Health Assessment for the 2008 Tronox Parcels A/B Soil Gas Investigation, Tronox LLC, Henderson, Nevada*, dated June 29, 2010, and *Errata to Revised Technical Memorandum: Screening-Level Indoor Air Health Assessment for the 2008 Tronox Parcels A/B Soil Gas Investigation, Tronox LLC, Henderson, Nevada: NDEP Facility ID # 000539.* August 31.

Northgate Environmental Management, Inc. (Northgate). 2010a. Health Risk Assessment Work Plan, Tronox Facility, Henderson, Nevada, March 2010.

Northgate Environmental Management, Inc. (Northgate). 2010b. Spring 2010 Indoor Air Quality Sampling and Analysis Report, Tronox LLC, Henderson, Nevada. September 22.

NRC. 1998. Chemical Mixtures. National Research Council, National Academy Press, Washington, DC.

Pacific Northwest National Laboratories (PNNL). 2001. Visual Sample Plan (VSP) Models and Code Verification. PNNL-13450. Prepared by R. O. Gilbert, J. R. Davidson, Jr., J. E. Wilson, B. A. Pulsipher. Prepared for the U.S. Department of Energy under Contract DE-AC06-76RL01830. February 2001

Risk Commission. 1997. Final report, Volume 2, Risk management in regulatory decision-making. Presidential/Congressional Commission of Risk Assessment and Risk Management, Washington, DC.

Seed, J., R.P. Brown, S.S. Olin, and J.A. Foran. 1995. Chemical mixtures: Current risk assessment methodologies and future directions. Regulatory Toxicol. Pharmacol. 22:76–94.

U.S. Environmental Protection Agency (U.S. EPA). 1986a. Guidelines for Carcinogen Risk Assessment. Risk Assessment Forum, Washington D.C. EPA/630/R-00/004. September

U.S. Environmental Protection Agency (U.S. EPA). 1986b. Guidelines for health risk assessment of chemical mixtures. U.S. Environmental Protection Agency, Federal Register 51(185):34104–34025.

U.S. Environmental Protection Agency (U.S. EPA). 1989. Risk Assessment Guidance for Superfund: Volume I—Human Health Evaluation Manual (Part A). Interim Final. Office of Emergency and Remedial Response, Washington, D.C. U.S. EPA/540/1-89/002. December.

U.S. Environmental Protection Agency (U.S. EPA). 1990. National Oil and Hazardous Substances Pollution Contingency Plan. U.S. Environmental Protection Agency, Federal Register 55:8666.

U.S. Environmental Protection Agency (U.S. EPA). 1992a. Guidelines for Exposure Assessment. Federal Register, 57(104):22888-22938. May 29.

U.S. Environmental Protection Agency (U.S. EPA). 1992b. Guidance for Data Usability in Risk Assessment. Part A. Office of Emergency and Remedial Response, Washington D.C. Publication 9285.7-09A. PB92-963356. April.

U.S. Environmental Protection Agency (U.S. EPA). 1992c. Guidance for Data Usability in Risk Assessment. Part B. Office of Emergency and Remedial Response, Washington D.C. Publication 9285.7-09B. PB92-963362. May.

U.S. Environmental Protection Agency (U.S. EPA). 1996. Proposed Guidelines for Carcinogen Risk Assessment. Office of Research and Development, Washington D.C. EPA/600/P-92/003C. April.

U.S. Environmental Protection Agency (U.S. EPA). 1997. Exposure Factors Handbook. Office of Research and Development, Washington DC. U.S. EPA/600/P-95/002Fa-c. August.

U.S. Environmental Protection Agency (U.S. EPA). 2002. Supplemental Guidance for Developing Soil Screening Levels for Superfund Sites. Office of Solid Waste and Emergency Response, Washington, DC. OSWER 9355.4-24. December.

U.S. Environmental Protection Agency (U.S. EPA). 2003. Memorandum on Human Health Toxicity Values in Superfund Risk Assessments, from Michael B. Cook, Director, Office of Superfund Remediation and Technology Innovation to Superfund Remediation Policy Managers, Regions 1 - 10, dated 5 December. OSWER Directive 9285.7-53.

U.S. Environmental Protection Agency (U.S. EPA). 2004. User's Guide for Evaluating Subsurface Vapor Intrusion into Buildings. Prepared by Environmental Quality Management, Inc. for the U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, Washington DC. February 22.

U.S. Environmental Protection Agency (U.S. EPA). 2009. Risk Assessment Guidance for Superfund Volume I: Human Health Evaluation Manual (Part F, Supplemental Guidance for Inhalation Risk Assessment) Final. EPA-540-R-070-002. January.

U.S. Environmental Protection Agency (U.S. EPA). 2010a. Regional Screening Level Table – User's Guide. http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/usersguide.htm. Accessed August 31.

U.S. Environmental Protection Agency (U.S. EPA). 2010b. Integrated Risk Information System. U.S. EPA on-line database: http://www.epa.gov/iris/index.html. Accessed August-November.